Fly ash-based Reactive Powder Concrete with coarse aggregate and GGBFS: mechanical properties and sustainability

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Abstract. This study examines the incorporation of ground granulated blast-furnace slag (GGBFS) into fly ash-based Reactive Powder Concrete (RPC) with coarse aggregate, aiming to enhance sustainability while preserving mechanical performance. The work focuses on optimizing flowability, strength, and carbon efficiency under standard curing conditions. The binder system comprised cement (33-55%) and GGBFS (0-22%), together with fixed proportions of fly ash (38%) and silica fume (8%) by weight. Results indicate that moderate GGBFS replacement improved both workability and strength, whereas higher replacement levels markedly reduced the carbon footprint. The RPC mixtures achieved flow values of 203-225 mm, 28-day compressive strengths ranging from 123.9 to 143.5 MPa, and flexural strengths between 20.1 and 24.4 MPa. Overall, the findings show that integrating GGBFS into fly ash-based RPC enables the development of low-carbon, cost-efficient, and high-strength concrete, offering strong potential for sustainable large-scale infrastructure applications.

1 Introduction

Reactive Powder Concrete (RPC), which is classified as an ultra-high strength ductile concrete or Ultra-High Performance Concrete (UHPC), has outstanding mechanical strength, ductility, and durability due to its optimized composition, mixing process, and post-set heat curing. To achieve a homogeneous microstructure, conventional RPC eliminates coarse aggregate, resulting in a high cement content (800-1,000 kg/m^3) and production costs, therefore limiting its use in large-scale infrastructure compared to conventional concrete [1].

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To address sustainability concerns, researchers have incorporated supplementary cementitious materials (SCMs), which are industrial by-products or naturally occurring materials such as limestone powder, metakaolin, fly ash and slag, to reduce the cement content and carbon footprint of RPC. Furthermore, incorporating coarse aggregate into RPC can reduce paste volume and total binder demand, offering additional cost and emission reductions while maintaining adequate performance, as its inclusion does not reduce the compressive strength of RPC [2].

Due to the high benefits of using fly ash (FA) in concrete industry, producing RPC with FA as the main SCM remains challenging. Moreover, studies on the effects of incorporating ground granulated blast-furnace slag (GGBFS) into FA-based RPC containing coarse aggregate are still limited. Addressing these gaps is significant because it would allow the development of low-carbon, cost-effective, and high-strength RPC suitable for large-scale structural applications.

Accordingly, this research aims to investigate the workability, compressive strengths (at 1, 3, and 28 days), flexural strength (at 28 days), and carbon footprint of RPC containing coarse aggregate and incorporating FA and GGBFS as partial cement replacements.

2 Literature review

Reactive Powder Concrete (RPC) is as an ultra-high strength ductile concrete, based on principles of optimized composition, mixing, and post-set heat curing. It was designed without coarse aggregate to achieve exceptional strength (exceeding 200 MPa) and durability. Its typical compositions include cement, silica fume, fine sand, superplasticizer, water, and steel fibers. Subsequent studies confirmed its superior mechanical and durability performance, resulting in a long service life with reduced maintenance. However, the absence of coarse aggregate led to high binder consumption (≈900 kg/m^3) and limited economic feasibility for large-scale infrastructure [1].

Collepardi et al. [2] demonstrated that introducing 8 mm coarse aggregates into RPC can enhance its mechanical performance, yielding higher strength and reduce shrinkage and creep, compared to conventional RPC. Shen et al. [3] demonstrated that carefully controlled incorporation of coarse aggregates (≤ 10 mm, up to 30% by volume) can improve both the strength and stiffness of UHPC. However, when the aggregate content is excessive content or particle size is too large, fiber dispersion and post-crack toughness are adversely affected. These findings highlight the need to select aggregate type, size, and dosage to achieve balanced mechanical performance.

Sustainability considerations have encouraged the partial replacement of cement with SCMs such as FA and GGBFS. FA is known to improve long-term strength and sulfate resistance, though it often slows early hydration [4, 5]. In contrast, GGBFS, with its latent hydraulic reactivity, refines pore structure, and significantly enhances chloride resistance [4], but may adversely affect workability [6]. While GGBFS is particularly effective in boosting compressive strength at later ages (28-90 days), improvements in flexural strength are generally less pronounced [7].

Recent investigations into hybrid FA-GGBFS systems have demonstrated superior sustainability outcomes compared with binders containing only FA. The combination of FA and GGBFS improves early-age strength, densified the microstructure, and achieves a more balance between mechanical performance and environmental impact [5]. In addition, life-cycle assessments indicated that UHPC incorporating SCMs can lower carbon emissions by as much as 55% relative to conventional UHPC [8].

Although notable progress has been made, most superior performance outcomes have been reported under steam or autoclave curing, conditions that are not feasible for in-situ construction. Research on ambient-cured RPC mixtures rich in FA and GGBFS and containing coarse aggregate remain limited. The available evidence suggests that combining coarse aggregate with SCMs in RPC can improve both sustainability and structural performance. However, assessments under ambient curing is still lacking. This gap provides the motivation for the present study.

3 Materials and methods

3.1 Materials

To facilitate practical field application, the materials selected for this study are commonly used in the concrete industry.

Fig. 1. Materials used in this study.

Table 1. Chemical compositions of the binders (mass %).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	LOI
C	13.32	2.73	3.54	74.37	0.89	3.50	0.28	0.49	0.26	0.12
SF	94.8	0.15	0.03	0.88	0.70	0.96	0.20	1.98	0.00	0.01
FA	53.03	16.97	6.22	15.69	0.78	4.09	0.35	1.27	0.98	0.05
GGBFS	29.6	15.4	0.32	40.3	9.34	2.19	0.46	0.42	1.32	0.12

Cement (C) is a hydraulic type produced by Siam Cement Group, Thailand, conforming to TIS 2594-2556 industrial standards [9] and ASTM C1157 Type GU specifications. Silica fume (SF) is an undensified product supplied by Eikem company, Thailand. Fly ash (FA), classified as Class F under ASTM C 618-15, is provided by Taurus Pozzolan Company, Thailand. Ground granulated blast-furnace slag (GGBFS) is grade 120 in accordance with ASTM C 989-99. Sand (S) is natural river sand in a saturated surface dry (SSD) condition, sourced from the Chi river, Thailand. Coarse aggregate (CA) consists of limestone with a nominal particle size of 8 mm. The superplasticizer (SP) used is of the polycarboxylate type. Water (W) is ordinary tap water. Steel fiber (STF) is a straight, mixed-size type with diameters ranging from 0.18 mm to 0.35 mm and lengths between 12 mm to 14 mm. Fig. 1 shows all materials utilized in this study, while Table 1 lists the main chemical compositions of the binder materials.

3.2 RPC Compositions and specimen preparation

To minimize binder consumption, carbon footprint, and overall material cost, facilitating large-scale application in infrastructure where economy and volume stability are as important as strength, RPC mixtures were designed with increased proportions of CA, FA, and GGBFS, while reducing SF content, as summarized in Table 2. In this study, a high-volume FA-based RPC incorporating coarse aggregate, capable of achieving compressive strengths exceeding 130 MPa under standard curing conditions, was further optimized for sustainability through partial replacement of cement with GGBFS. The binder (B) consisted of C ranging from 33% to 55% and GGBFS from 0% to 22%, combined with fixed proportions of FA (38%) and SF (8%) by weight.

Specimen preparation was carried out using a concrete pan mixer. The binders (C, SF, FA, and GGBFS) was first blended with sand and divided into two portions. The initial portion of this dry mix was combined with part of the premixed liquid (W and SP), followed by the addition of the first fraction of coarse aggregate (CA). The remaining binder-sand mixture, premixed liquid, and CA were then introduced sequentially. In the final stage, steel fibers (STF) were incorporated. Continuous mixing was maintained throughout to ensure a uniform and homogeneous composition. After mixing, the workability of RPC was assessed by measuring flow value in accordance with ASTM C 1437, without using a drop table. The fresh mixtures were cast into steel molds and immediately sealed with plastic sheeting to prevent moisture loss. Specimens were demolded after 24 hours and subsequently cured in water at room temperature until the designated testing age.

Table 2. Mix compositions (wt. ratio).

Mix code	Binder[1]	C	SF	FA	GGBFS	W	SP	S	CA	STF
FA38GS0	1	0.55	0.08	0.38	0	0.18	0.04	0.48	0.44	0.15
FA38GS5	1	0.49	0.08	0.38	0.05	0.18	0.04	0.48	0.44	0.15
FA38GS22	1	0.33	0.08	0.38	0.22	0.18	0.04	0.48	0.44	0.15

[1] Binder is C+SF+FA+GGBFS.

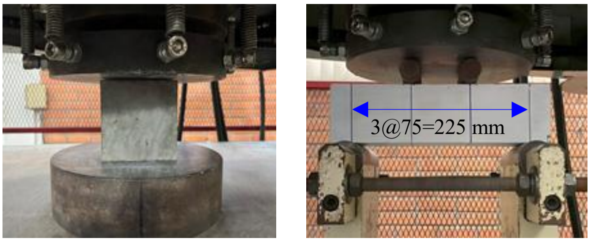
3.3 Testing and analysis

Mechanical performance was evaluated by measuring compressive strengths at 1, 3, and 28 days, together with flexural strength at 28 days. The specimen sizes and relevant testing standards are presented in Table 3. The setups for each test are shown in Fig. 2.

Table 3. Details of the tests.

Strength test	Specimen size (mm)	Testing age	Specimens per test	Standard
Compressive	100 cube	1, 3, 28 days	3	BS 1881-116
Flexural	75×75×280 prism	28 days	3	ASTM C78

The carbon footprint of each mixture, defined as the total CO_2 emissions from all RPC constituents per unit volume, was evaluated to determine its environment impact. In addition, a carbon index (CI) was calculated by normalized the carbon footprint against the corresponding 28-day compressive strength, allowing for a strength-adjusted comparison of environmental performance. For this assessment, emission factors related to embodied CO_2 generated during the material production was applied, while transportation and mixing processes were excluded, as summarized in Table 4.



(a) Compression test (b) Flexure test

Fig. 2. Setups of the compression and flexural tests.

Table 4. Emission factors of materials.

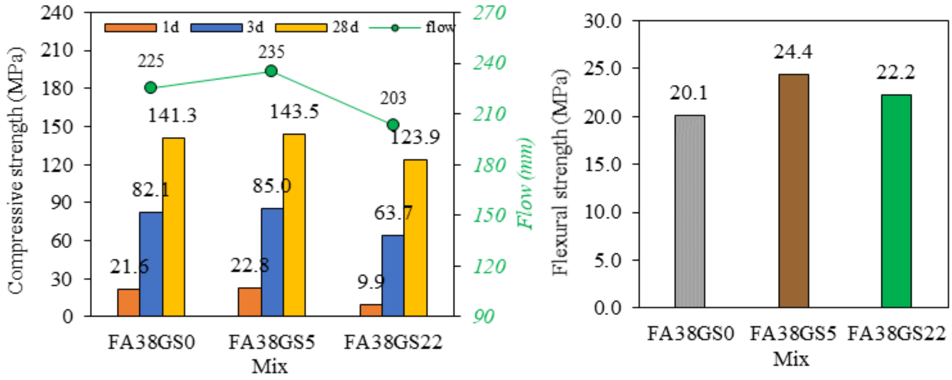
Material	C	SF	FA	GGBFS	W	SP	S	CA	STF
Emission factor (kg·C0$_2$·e/kg)	0.724	0.014	0.009	0.019	0.0003	0.72	0.01	0.0459	1.4965
Reference	[9]	[10]	[11]	[10]	[10]	[10]	[10]	[12]	[10]

4 Results and discussion

4.1 Flow and compressive strength

Fig. 3(a) presents the flow values and compressive strengths of FA-based RPC mixtures containing different proportions of GGBFS. The highest flow, 235 mm, was recorded for Mix FA38GS5 (5% GGBFS), showing that a moderate GGBFS addition improves the workability of FA-based RPC with coarse aggregate. This improvement is attributed to the smooth and dense surfaces of GGBFS particles, which absorb less water than cement and thereby promote greater fluidity [13]. These results contribute to closing the research gap regarding the influence of GGBFS on the workability of FA-based systems. In contrast, when the GGBFS content was raised to 22% (Mix FA3G22), the flow dropped to 203 mm, indicating that excessive GGBFS makes the mixture stiffer through accelerated hydration and increased viscosity. Comparable trends have been observed in FA-based geopolymer concretes, where higher GGBFS replacement levels (10-40%) reduced workability due to rapid setting and higher reactivity [6].

All mixtures showed a steady gain in compressive strength with increasing curing age. At 28 days, strength rose from 141.3 MPa in Mix FA38GS0 to 143.5 MPa in Mix FA38GS5, indicating that a small addition of GGBFS enhances performance through supplementary pozzolanic and latent hydraulic reactions, which refine the pore structure and strengthen the matrix [4]. When the GGBFS content was raised to 22%, however, strength declined to 123.9 MPa, likely due to excessive slag reducing binder reactivity and overall packing density [14]. Taken together, the inclusion of 5% GGBFS provided the most favorable balance between workability and compressive strength, showing that limited replacement of fly ash with GGBFS can improve both fresh and hardened properties of FA-based RPC containing coarse aggregate.



(a)

(b)

Fig. 3. Test results: (a) Flow values and compressive strengths; (b) Flexural strengths.

4.2 Flexural strength

Fig. 3(b) shows that the 28-day flexural strength results mirrored the trend observed in compressive strength. The highest value, 24.4 MPa, was obtained for Mix FA38GS5 (5% GGBFS), indicating that a moderate level of GGBFS enhances the flexural performance of FA-based RPC. This improvement arises from both chemical and physical mechanisms: GGBFS promotes the formation of additional calcium silicate hydrate (C-S-H) through secondary hydration, while its fine particles fill voids in the matrix, producing a denser and more cohesive microstructure [7].

At a GGBFS content of 22% (Mix FA3G22), the flexural strength declined slightly to 22.2 MPa, though it remained above that of the mix without GGBFS (20.1 MPa). The reduction observed at higher GGBFS levels may be attributed to increased matrix stiffness and limited calcium availability for complete hydration, conditions that can promote microcracking under flexural loading [15]· Overall, the findings reinforce that a moderate GGBFS content (≈ 5%) provided the most effective balance for enhancing both strength and ductility in FA-based RPC systems.

4.3 Carbon footprint and carbon index

Fig. 4 shows the carbon footprint and carbon index (CI) of the FA-based RPC mixtures. Both parameters decreased consistently as the GGBFS content increased. The lowest values, 552.9 kg·CO$_2$·e/m^3 for carbon footprint and 4.46 kg·CO$_2$·e/m^3/MPa for CI, were recorded in Mix FA38GS22 (22% GGBFS), representing a 23% reduction compared with Mix FA38GS0 (717.2 kg·CO$_2$·e/m^3, CI = 5.08). These results demonstrate that replacing part of the cement with GGBFS can markedly lower embodied carbon emissions while still ensuring satisfactory mechanical performance.

The decrease in carbon footprint is mainly due to the reduced clinker content and the energy-efficient production of GGBFS, which consumes less thermal energy than cement [10]. These results highlight the promise of GGBFS as a sustainable SCM for advancing low-carbon RPC.

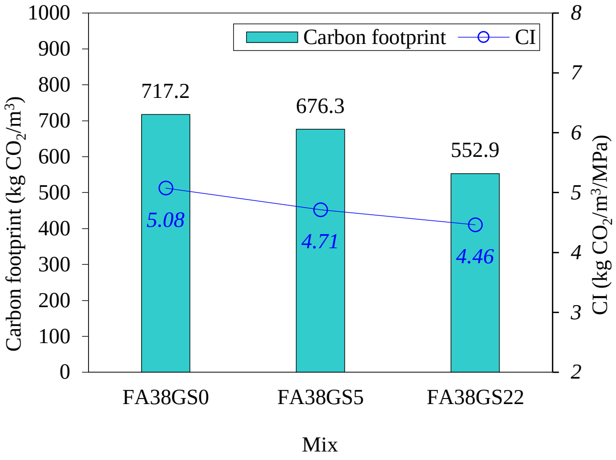


Fig. 4. Carbon footprint and carbon index (CI) of each mixture.

5 Conclusion

This study examined the effects of ground granulated blast-furnace slag (GGBFS) on the flowability, mechanical properties, and carbon footprint of fly ash-based Reactive Powder Concrete (RPC) containing 8 mm coarse aggregate under standard curing conditions. The binder system consisted of cement (33-55%) and GGBFS (0-22%), with fixed fly ash (38%) and silica fume (8%) by weight. Test results showed that partial substitution of cement with GGBFS significantly lowered embodied carbon emissions while maintaining, and in some cases enhancing, the mechanical properties of FA-based RPC. A moderate GGBFS content delivered the best balanced between workability and strength, with 5% GGBFS achieving a flow of 235 mm, a 28-day compressive strength of 143.5 MPa, and a flexural strength of 24.4 MPa. The lowest carbon footprint of 552.9 kg·CO_2·e/m^3 and carbon index (CI) of 4.46kg·CO_2·e/m^3/MPa were obtained at 22% GGBFS, corresponding to a 23% reduction compared with the control mix.

Overall, the combined use of fly ash and GGBFS in RPC with coarse aggregate demonstrates a promising pathway toward developing low-carbon, cost-efficient, and high-strength RPC suitable for large-scale structural applications. Future research should extend beyond early-age performance to explore long-term mechanical and durability properties, microstructural evolution, and life-cycle cost analysis under practical curing and exposure conditions, to fully realize the potential of FA-GGBFS-based RPC in sustainable infrastructure.

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