Journal of Engineering and Sustainable Development
Vol. 30, No. 01, January 2026
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.2227

Effect of Acid Attack on the Performance of Reactive Powder Concrete Incorporating Supplementary Cementitious Materials

Mohammed Saad Elhussainy*, Eman Kh. Ibrahim

Civil Engineering Department, College of Engineering, University of Mosul, Mosul City, Iraq

*Email: mohammed.21enp70@student.uomosul.edu.iq

Article Info

Received	14/11/2023
Revised	05/12/2025
Accepted	07/12/2025

Abstract

Evaluating the effect of acid attack on concrete performance in harsh environments has been interesting for many researchers. This study investigated the effect of supplementary cementitious materials (SCMs) on improving the acid resistance of reactive powder concrete (RPC). Three RPC mixes, including a control, a mixture with 25% replacement of cement by fly ash, and a mixture with 25% replacement of cement with slag, were exposed to a 3% sulfuric acid solution. The deterioration of RPC was evaluated based on mechanical properties and weight loss. The results indicate that RPC mixtures containing fly ash or slag could improve their acid resistance. Slag induced the best acid resistance among 3-day cured mixtures, with 28% and 26% compressive and tensile strength loss, respectively. At the same time, fly ash induced the best acid resistance among 28-day cured mixtures, with a 29% compressive and tensile strength loss. The control mixture exhibited the highest weight loss after 56 days of exposure, with 22% and 14% for 3 and 28 days of curing, respectively, compared to other mixtures containing fly ash or slag, indicating that the use of SCMs can improve the resistance of RPC to sulfuric acid and enhance its durability.

Keywords: Acid attack, Concrete deterioration, Durability, Reactive powder concrete, Sulfuric acid, Supplementary cementitious materials.

1. Introduction

Concrete's resistance to aggressive chemical attacks from external sources is a significant characteristic affecting its durability and a major factor contributing to concrete deterioration [1]. Acid attacks, common in sewerage manholes, areas affected by acid rain, and surfaces in contact with acids, weaken concrete, leading to erosion and strength loss [2], as depicted in Figs. 1 and 2. To address this issue, the study used reactive powder concrete (RPC), an ultra-high-strength cement composite with improved mechanical properties and superior acid resistance [3]. However, the high cement content in RPC raises environmental concerns, specifically increased CO_2 emissions [4], prompting the need for further investigation.

Figure 1. The effects of sulfuric acid on the floor of an acid storage warehouse in the industrial area on the left side of the city of Mosul.

Figure 2. Erosion effects on concrete were observed in a manhole in the Al Nabi-Yunus area, on the left side of Mosul.

Several studies have investigated the performance of concrete under acid attack. Among these, Barbhuiya and Kumala [5] investigated the behavior of concrete containing fly ash and ultra-fine fly ash in sulfuric and nitric acid. They found that replacing 30% of the cement weight with fly ash and 10% with ultra-fine fly ash decreased the loss of compressive strength and mass after exposure to the acids. Rao et al. [6] investigated the acid resistance of Quaternary Blended Cement Concrete (QBCC) incorporating recycled aggregate. They exposed QBCC to two acids, sulfuric and hydrochloric, and observed that the use of recycled aggregate enhances the acid resistance of concrete. Torres et al. [7] investigated the impact of sulfuric acid on high-performance concrete (HPC). They observed that concrete specimens with lower cement content exhibited greater resistance to sulfuric acid than those with higher cement content. Aygörmez and Canpolat [8] examined the impact of sulfuric and hydrochloric acid on geopolymer composites, finding that sulfuric acid has a more substantial damaging effect on geopolymer composites than hydrochloric acid. Dhundasi et al. [9] investigated the durability properties of RPC under sulfuric acid attack. Their results showed that the strength and mass of the specimens decreased significantly at high sulfuric acid concentrations. Youssari et al. [10] investigated the effect of metal fibers on concrete in harsh environments. Concrete specimens, with and without fibers, were exposed to 5% concentrated hydrochloric acid, sulfuric acid, and acetic acid for a duration of 135 days. The study revealed that incorporating metal fibers reduces porosity by 14%, enhancing the mechanical strength of concrete. Arjomandi et al. [11] investigated the acid resistance of concrete using steel fibers and recycled nylon granules as sand substitutes. They found that the optimal mix for maximum 90-day compressive strength under acid exposure is 0.11% steel fibers and 20% nylon granules, supporting cleaner and more sustainable concrete. Shariati et al. [12] examined coal waste (CW) as a replacement for concrete aggregate. They observed that higher CW content increased water absorption and weight loss, causing continuous strength reduction under sulfuric acid exposure.

This research aims to evaluate the reduction of cement content in RPC by incorporating supplementary cementitious materials (SCMs) such as granulated ground blast-furnace slag (GGBS), fly ash, and silica fume. The evaluation is based on RPC's performance against acid attacks. Since the city of Mosul works to enhance its infrastructure, the officials sometimes need to temporarily redirect water flow after 3 days of casting, as shown in Fig. 3, excavate trenches, install sewage pipes, and cast manholes, resulting in the exposure of newly cast manholes to acidic water within a short span.

Figure 3. Temporarily changing the water pathway as part of a sewage project in the Al-Islah Al-Zira'i Neighborhood, Mosul City, Iraq.

This study investigates the effects of such exposure by conducting tests on specimens subjected to acid after a 3-day curing period in water, simulating real-time conditions, in addition to the standard 28-day curing period.

2. Experimental Program

2.1. Materials

Cement: Ordinary Portland Cement (OPC) supplied by "Mass Cement Factory" was used in all mixtures, conforming to Iraqi specification IQS No. 5/2019 [13]. The cement has a specific gravity of 3.15. The chemical composition analysis of the cement is presented in Table 1, and its physical properties are provided in Table 2.

Table 1. Chemical composition analysis of cementitious raw materials (value %).

Chemical Composition	Cement	Silica Fume	Fly-Ash	*GGBS*
SiO_2	19.5	95	47.67	31.86
Al_2O_3	4.9	1.38	27.73	16.67
Fe_2O_3	3.29	0.02	15.42	0.86
CaO	64.25	0.018	5.11	38.72
MgO	3.04	0.01	2.65	8.41
SO_3	2.64	0.3	0.34	0.72
Free Lime	1.32	-	-	-
Loss on ignition	2.06	1.05	3.71	0.2
Insoluble residue	0.75	-	-	-

Table 2. Physical properties of cement.

Physical Properties	Test Results	Limits of IQS No. 5/2019
Standard Consistency (w/c)	0.27	----
Initial Setting Time (min.)	150	≥ 45 min
Final Setting Time (hrs.)	5	≤ 10 hrs.
Compressive strength at:		
2 days (MPa)	17.9	≥ 10
28 days (MPa)	41.2	≥ 32.5
Fineness, Blain method (m^2/kg)	331	≥ 250

Silica Fume (SF): Micro-silica fume supplied by "ECA Company" is a dry, densified ultra-fine powder with a specific gravity of 2.25, conforming to ASTM C1240-20 [14]. It was used at 10% by weight of cementitious materials (CMs). The chemical properties of silica fume are listed in Table 1.

Fly Ash (FA): Fly ash type F supplied by "Euro Build Company" with a specific surface area of 360 m^2/kg and a specific gravity of 2.4, conforming to ASTM C-618-19 standards [15]. It was used as a 25% replacement for cement by weight. The chemical properties of fly ash are listed in Table 1.

GGBS: Slag, which is a light grey powder obtained as a by-product of iron manufacturing from "Songhe Industrial Company" in China. Slag complies with the requirements of BS EN 15167-1 [16]. In China, the slag, also known as GGBS, is classified into three grades: S75, S95, and S105 [17]. In this study, grade S95, with a specific surface area of 418 m2/kg and a specific gravity of 2.9, was used as a 25% replacement for cement by weight. Table 1 provides the chemical properties of the slag.

Fine Sand: Natural river sand from the "Nineveh zone" with a specific gravity of 2.65 and 1.42% absorption was used. The grading of the sand is presented in Table 3.

Table 3. Grading and Fineness Modulus of RPC Sand.

Sieve size	Cumulative weight retained (gm)	Passing %
4.75 mm	0	100
2.36 mm	0	100
1.18 mm	0	100
0.6 mm	0	100
0.3 mm	52.8	47.2
0.15 mm	100	0
Fineness Modulus		**1.528**

Quartz Powder (QP): Quartz powder with a bulk density of 1584 kg/m^3 from "KÖSTER company" was utilized.

Superplasticizer (SP): "Hyperplast PC200" is a high-performance superplasticizer with a specific gravity of 1.05. It was used at a dosage of 1.5% weight of the CMs for all mixtures.

Polypropylene Fiber (PP fiber): PP fiber with a length of 9mm from "Sika Company" was added to all concrete mixtures in this study. The fiber has a density of 0.91 g/cm³ and was incorporated at a dosage of 0.15% by weight relative to the CMs in all mixtures. Fig. 4 shows the materials used for RPC.

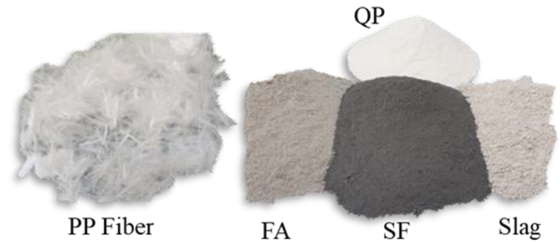

Figure 4. Materials Used for RPC: Silica Fume, Fly Ash, GGBS Slag, Quartz Powder, and PP Fiber.

2.2. Mix Proportions

All reactive powder concrete (RPC) mixtures were prepared with a cementitious material (CM) content of 968 kg/m3, incorporating 10% silica fume by weight of the CMs. The mixtures included RPC-C as the control, RPC-FA with a 25% replacement of cement weight using fly ash type F, and RPC-S with a 25% replacement using GGBS. All mixtures contained polypropylene fiber (pp) of 0.15% weight of the CMs, superplasticizer (SP) of 1.5% weight of the CMs, and a water-to-cementitious materials ratio *(w/cm)* of 0.25. The details of the mixtures are presented in Table 4.

Table 4. Composition of RPC mixtures.

RPC	RPC-C	RPC-FA	RPC-S
Cement kg/m³	871	653	653
Sand kg/m³	871	871	871
QP kg/m³	290	290	290
SF kg/m³	97	97	97
FA kg/m³	0	218	0
GGBS kg/m³	0	0	218
w/cm	0.25	0.25	0.25
PP Fiber %	0.15	0.15	0.15
SP %	1.5	1.5	1.5

2.3. Mixing and Preparing Specimens

The mixing procedure for RPC involved weighing and combining the cementitious components, mixing them to achieve uniformity, adding water, superplasticizer, and PP fiber, and mixing for 13 minutes. The workability of the mixture was tested using the ASTM C 1437 method [18]. Then, the mixture was poured into molds and compacted using a vibrating table. The specimens were covered with a plastic sheet and cured in a laboratory at 22 ± 3°C. After 24 hours, the specimens were taken out of the molds, divided into two groups, and placed in a water tank for curing. One group was cured for 3 days, and the other was cured for 28 days. Subsequently, the specimens were immersed in sulfuric acid for two different exposure periods of 28 or 56 days.

The sulfuric acid used has a concentration of 3% and a pH of approximately 0.85. It is changed when there is a noticeable change in pH, typically every two weeks. The acid is stored in two polyethylene basins, one for cube specimens and the other for cylinder specimens. Fig. 5 shows the two basins used for RPC specimens.

Figure 5. Sulfuric acid basins.

2.4. Experimental Work Procedure

The previously mentioned procedures regarding the practical aspects of this study are further illustrated through the step-by-step process outlined in the flowchart shown in Fig. 6.

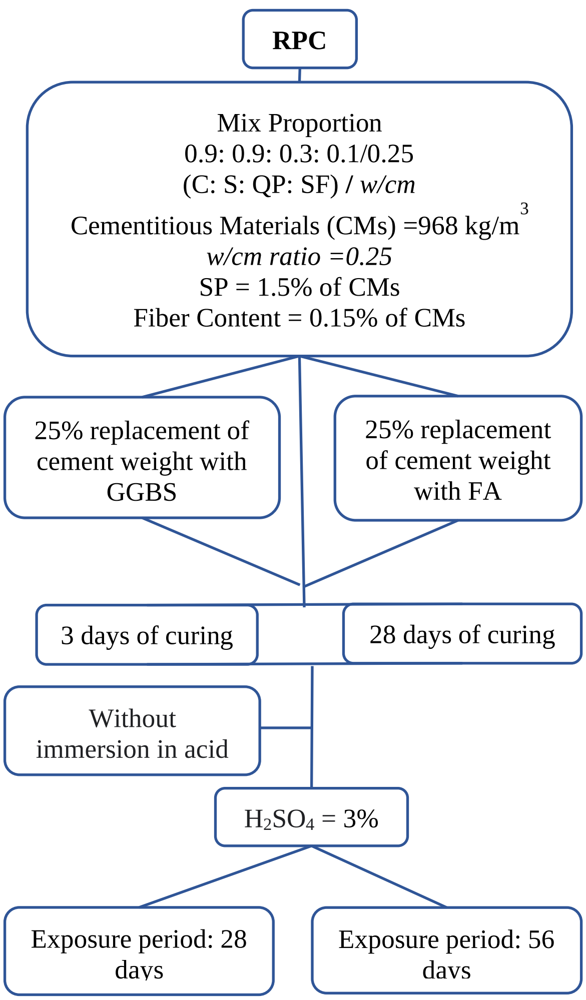

Figure 6. Experimental work procedure.

2.5. Testing Methods

The fresh concrete mixtures were tested for flow rate, and the hardened concrete specimens were evaluated for acid resistance based on compressive strength, splitting tensile strength, weight loss, and ultrasonic pulse velocity.

- **Compressive Strength**

A total of 54 cubic specimens (100 x 100 x 100 mm) were tested for compressive strength (18 cubes for each mix). The test followed the guidelines stated in BS EN 12390-3:2019 [19] as shown in Fig.7. The specimens were cured for two different periods: either 3 or 28 days before exposure to the acid for two periods of 28 and 56 days. The compressive strength of each mix at each age was measured as the average strength of three specimens. The percentage reduction in compressive strength of the specimens was calculated using (1).

$$\%\ Strength\ loss = \frac{fi - fs}{fi} * 100 \quad (1)$$

Where *fi* represents the initial strength before exposure to acid (in MPa), and *fs* represents the strength after exposure to acid (in MPa).

Figure 7. Compressive strength test.

- **Splitting Tensile Strength**

A total of 54 cylindrical specimens (100 x 200 mm) were tested for splitting tensile strength (18 cylinders for each mix). The test followed the specifications outlined in ASTM C496 [20], as shown in Fig. 8. It involved applying a compressive force along the cylinder's length at a rate of 0.02 kN/s. The specimens were cured for 3 or 28 days before exposure to acid, with subsequent exposure for 28 or 56 days. The splitting tensile strength of each mix at each age was measured as the average strength of three specimens. The percentage reduction in the splitting tensile strength value was calculated using (1).

Figure 8. Splitting tensile strength test.

- **Total Weight Loss**

To measure total weight loss, the specimens are dried in an oven at 105°C for 24 hours at the end of curing periods (3 days or 28 days). The initial weight of the specimens is measured before immersing them in a sulfuric acid solution. After the exposure periods, the specimens were removed from the acid, cleaned with a wire brush, dried in an oven at 105°C for 24 hours, and weighed as the final weight. The percentage of total weight loss was calculated using (2).

$$\%\,Total\ weight\ loss = \frac{Wi - Ws}{Wi} * 100 \qquad (2)$$

Where *Wi* represents the initial weight before exposure to acid (in grams), and *Ws* represents the weight after exposure to acid (in grams).

- **Ultrasonic Pulse Velocity Test**

The ultrasonic pulse-velocity test was conducted in accordance with the guidelines of ASTM C597-16 [21] to assess the quality of the concrete, as shown in Fig. 9. Cube specimens of 100 x 100 x 100 mm were used for this test. The test was conducted on specimens immersed in acid for 56 days. The velocities of the ultrasonic pulses were measured, and the concrete quality was evaluated based on the ultrasonic velocities [22], as outlined in Table 5.

Figure 9. Ultrasonic pulse velocity test.

Table 5. Concrete quality classification based on pulse velocity [22].

Velocity (km/sec)	Concrete quality
> 4.58	Excellent
3.4 - 4.5	Good
3.0 - 3.5	Doubtful
2.0 - 3.0	Poor

3. Results and Discussion

3.1. Flow Rate

The addition of supplementary cementitious materials (SCMs), such as fly ash or GGBS, enhances the workability and flow characteristics of fresh concrete, as shown in Table 6. The incorporation of fly ash reduces the water demand in RPC, thereby improving workability. This enhancement occurs without affecting the water-to-binder ratio or superplasticizer dosage. The spherical shape, smooth texture, and fine particle size of fly ash contribute to this effect [23], [24]. While the inclusion of GGBS enhances workability by absorbing less water during mixing, due to its smooth, dense surface [24],[25].

Table 6. Flow rate (%) results.

RPC Mixtures	Flow Rate (%)
RPC-C	84.1
RPC-FA	90.9
RPC-S	113.6

3.2. Compressive Strength Loss

The results of the compressive strength of concrete specimens for the mixtures RPC-C, RPC-FA, and RPC-S that were cured in water for 3 days and exposed to the acid solution for 0, 28, and 56 days are shown in Fig. 10. For 28 days of exposure, a slight difference in the strength loss was observed among the three mixtures; RPC-C, RPC-FA, and RPC-S exhibited a 22%, 21%, and 19% loss in strength, respectively. After 56 days of exposure, the difference in strength loss was more obvious among the three mixtures. RPC-C, RPC-FA, and RPC-S exhibited a 39%, 34%, and 28% loss in strength, respectively.

The results of the compressive strength of concrete specimens for the mixtures RPC-C, RPC-FA, and RPC-S that were cured in water for 28 days and exposed to the acid solution for 0, 28, and 56 days are shown in Fig. 11. For 28 days of exposure, no significant difference in the strength loss was observed among the three mixtures; RPC-C, RPC-FA, and RPC-S exhibited a 21%, 18%, and 17% loss in strength, respectively. However, after 56 days of acid exposure, RPC-C, RPC-FA, and RPC-S exhibited 44%, 29%, and 38% reductions in strength, respectively. The results show that RPC-S specimens exhibited the best performance when cured for 3 days and exposed to the acid for 56 days, compared with RPC-FA and RPC-C specimens. While RPC-FA specimens exhibited the best performance when cured for 28 days and exposed to the acid for 56 days, compared with RPC-C and RPC-S specimens, as shown in Table 7.

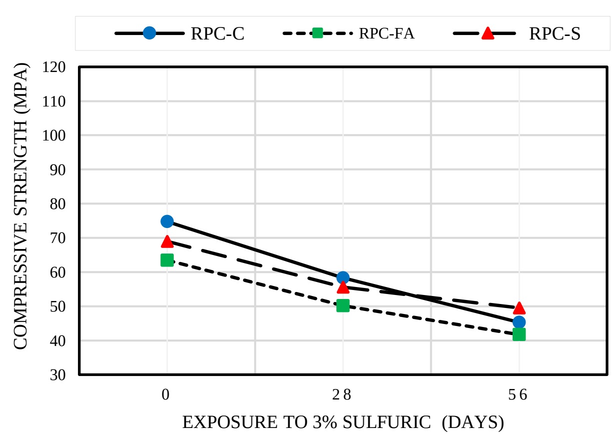

Figure 10. Effects of acid exposure on the compressive strength of 3-day-cured RPC specimens.

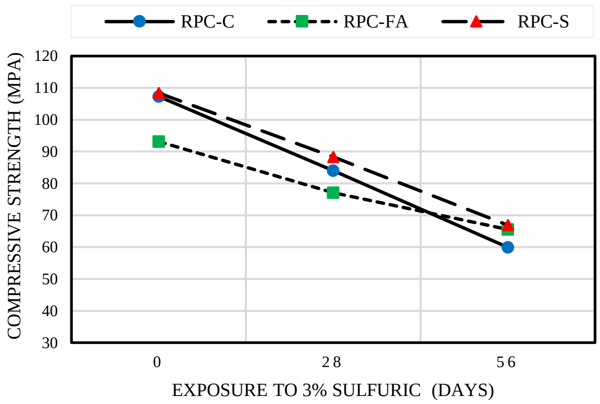

Figure 11. Effects of acid exposure on the compressive strength of 28-day-cured RPC specimens.

Table 7. Differences in the rate of compressive strength loss among RPC mixtures.

Curing (days)		3	3	28	28
Exposure to acid (days)		28	56	28	56
% Strength loss	RPC-C (control)	22	39.4	21.7	44.1
	RPC-FA	21	34.3	17.2	29.6
	RPC-S	19.4	28.2	18.5	38.3
% Difference between RPC-C and RPC-FA		5	13.9	23.2	39.3
% Difference between RPC-C and RPC-S		12.9	33.1	15.9	14.2

3.3. Splitting Tensile Strength Loss

The results of splitting tensile strength loss for the specimens of the mixtures RPC-C, RPC-FA, and RPC-S that were cured in water for 3 days and exposed to the acid attack for 0, 28, and 56 days are shown in Fig. 12. For 28 days of exposure, RPC-C, RPC-FA, and RPC-S exhibited a 19%, 18%, and 17% loss in strength, respectively. After 56 days of acid exposure, RPC-C, RPC-FA, and RPC-S exhibited a 33%, 29%, and 26% loss in strength, respectively. The results show that the strength loss between mixtures was slightly apparent after 56 days of exposure.

Fig. 13 shows the results of the splitting tensile strength loss for the specimens of the mixtures RPC-C, RPC-FA, and RPC-S that were cured in water for 28 days and exposed to the acid solution for 0, 28, and 56 days. For 28 days of exposure, RPC-C, RPC-FA, and RPC-S exhibited a 21%, 16%, and 18% loss in strength, respectively. After 56 days of exposure to the acid, RPC-C, RPC-FA, and RPC-S exhibited a 36%, 29%, and 31% loss in strength, respectively. The results show that RPC-S specimens exhibited the best performance when cured for 3 days and subsequently exposed to acid for 56 days, compared with RPC-FA and RPC-C specimens. While RPC-FA specimens exhibited the best performance when cured for 28 days and exposed to the acid for 56 days, compared with RPC-C and RPC-S specimens, as shown in Table 8.

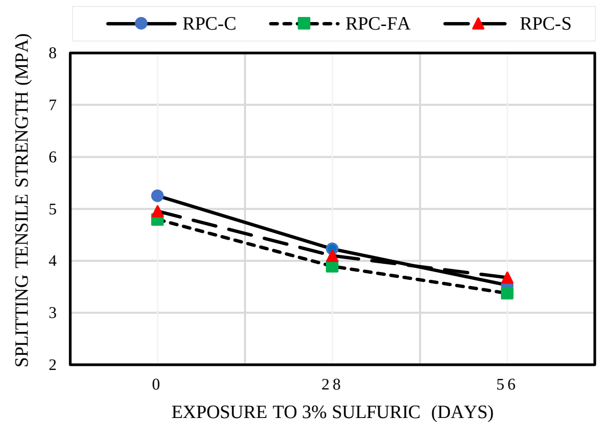

Figure 12. Effects of acid exposure on the splitting tensile strength of 3-day-cured RPC specimens.

3.4. Total Weight Loss

Fig. 14 represents the total weight loss of the specimens cured for 3 days and immersed in the acid solution for 28 and 56 days. RPC-C specimens experienced an average weight loss of 14.95% after 28 days and increased to 22.13% after 56 days. RPC-FA specimens showed slightly lower weight loss, with an average of 13.80% after 28 days and 19.70% after 56 days. RPC-S exhibited a trend similar to RPC-FA, with an average weight loss of 10.33% after 28 days and 16.29% after 56 days. Fig. 15 represents the total weight loss of the specimens cured for 28 days and immersed in the acid solution for 28 and 56 days. RPC-C specimens experienced an average weight loss of 7.01 % after 28 days and increased to 14.52 % after 56 days. RPC-FA specimens showed slightly lower weight loss, with an average of 4.16 % after 28 days and 11.98 % after 56 days. At the same time, RPC-S exhibited a trend similar to RPC-FA, with an average weight loss of 5.07% after 28 days and 11.46% after 56 days. As shown in Table 9, RPC-S mixtures exhibited less weight loss than the other mixtures.

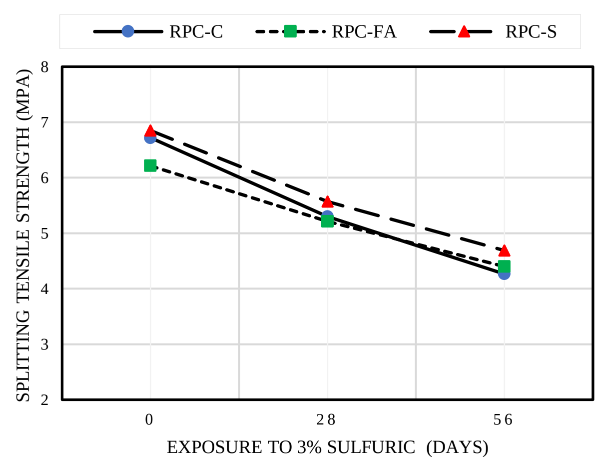

Figure 13. Effects of acid exposure on the splitting tensile strength of 28-day-cured RPC specimens.

Table 8. Differences in splitting tensile strength loss between RPC mixtures.

Curing (days)		3	3	28	28
Exposure to acid (days)		28	56	28	56
% Strength loss	RPC-C (control)	19.5	32.7	21.2	36.5
	RPC-FA	18.7	29.6	16.1	29.2
	RPC-S	17.3	25.8	18.7	31.6
% Difference between RPC-C and RPC-FA		4	9.9	27.2	22.3
% Difference between RPC-C and RPC-S		11.9	23.7	12.4	14.6

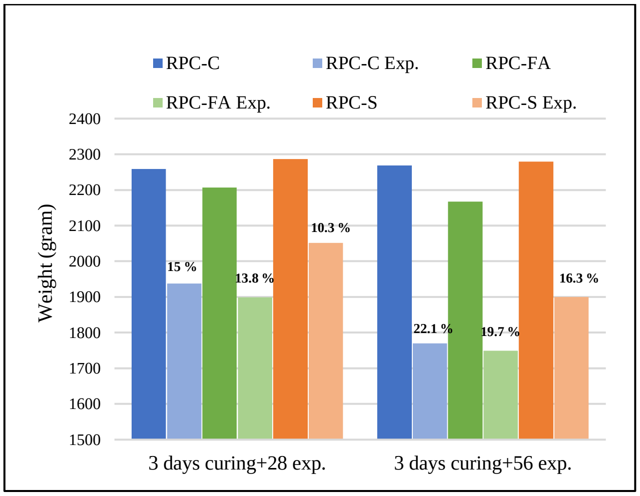

Figure 14. Effects of acid exposure on the weight of 3-day-cured RPC specimens.

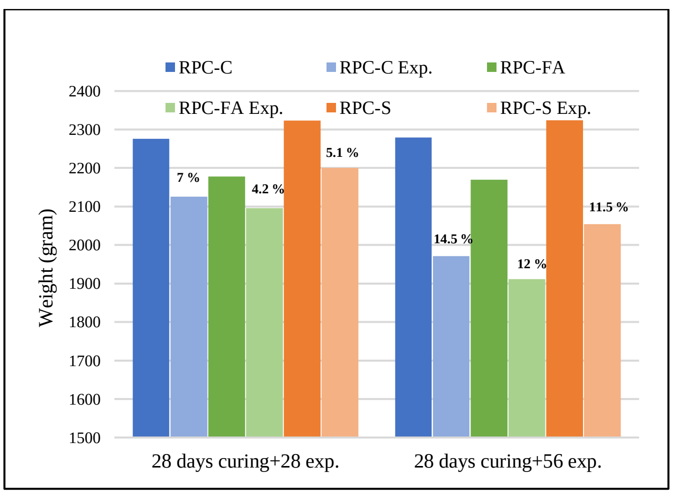

Figure 15. Effects of acid exposure on the weight of 28-day-cured RPC specimens.

Table 9. Differences in weight loss between RPC mixtures.

Curing (days)		3	3	28	28
Exposure to acid (days)		28	56	28	56
% Total weight loss	RPC-C (control)	14.95	22.13	7.01	14.52
	RPC-FA	13.8	19.7	4.2	12
	RPC-S	10.3	16.3	5.1	11.5
% Difference between RPC-C and RPC-FA		8	11.6	51	19.2
% Difference between RPC-C and RPC-S		36.6	30.4	32.1	23.6

The effect of the acid on the specimens is evident in Fig. 16.

Figure 16. a. RPC-C cylinder specimens before and after exposure to sulfuric acid for 56 days. b. RPC-C cubic specimens after immersion in sulfuric acid.

3.5. Ultrasonic Pulse Velocity

The velocity results of all mixtures after a 56-day exposure to sulfuric acid are presented in Table 10. RPC-S specimens show the highest velocity result of 4.639 km/sec compared to the other specimens with a 3-day curing period. On the other hand, RPC-FA demonstrates the best velocity result of 4.834 km/sec for specimens cured for 28 days. These findings indicate that even after 56 days of exposure to the acid, RPC-S specimens remained in excellent quality when cured for 3 days, while RPC-FA specimens remained in excellent quality when cured for 28 days.

Table 10. Ultrasonic-velocity values.

RPC Mixtures	Velocity (km/s) 3 curing + 56 exp.	Velocity (km/s) 28 curing + 56 exp.
RPC-C	3.922	4.130
RPC-FA	4.047	4.834
RPC-S	4.639	4.180

3.6. Discussion

The results of this study highlight distinct variations in the acid resistance performance of three different reactive powder concrete (RPC) mixtures. Among them, RPC-Control, which solely contained silica fume without supplementary cementitious materials, exhibited less resistance to acid attack compared to the other mixtures that incorporated GGBS or fly ash. This disparity was observed in both groups of specimens, cured for 3 days and 28 days. The inferior acid resistance of RPC-C can be attributed to its higher cement content, which renders it more susceptible to acid damage. On the contrary, the use of supplementary cementitious materials, with a 25% replacement of cement weight, showed positive effects on the concrete's acid resistance.

The mixture containing GGBS (RPC-S) demonstrated significant improvements when subjected to acid exposure. It exhibited minimal detrimental effects in terms of weight loss, compressive strength, and tensile strength, particularly for the group of specimens cured in water for 3 days. The superior acid resistance of RPC-S can be attributed to the reduction in voids and pore size achieved through the inclusion of GGBS in the concrete, leading to lower porosity [26]-28]. This reduction in porosity resulted in enhanced acid resistance. During the initial hydration process, the calcium hydroxides released by Portland cement reacted with the GGBS, causing a breakdown of its glassy structure. As hydration continued, more calcium hydroxides precipitated and formed calcium silicate hydrate (CSH), which filled the pores, thereby enhancing strength and chemical resistance and refining the pore size [29]. In general, concrete with GGBS content exhibits good resistance to acid attack, both during the early and later stages of concrete development, due to the denser structure and decreased permeability [17],[29].

On the other hand, the mixture containing fly ash (RPC-FA) had a slower rate of hydration [30],[31], resulting in weaker acid resistance compared to (RPC-S) during the initial stages of concrete development. This slower reaction rate of fly ash particles contributed to the diminished acid resistance. Additionally, at early ages, fly ash concrete exhibited lower levels of calcium silicate hydrate gel (C-S-H) and higher porosity, making it less resistant to sulfuric acid attack [32],[33]. Over time, fly ash in concrete has contributed to increased C-S-H formation through its pozzolanic reactivity. This, in turn, reduces the interconnected voids as the binder material hydrates. Consequently, decreased capillary and gel pores, along with reduced interconnected voids due to its fine particles [31], [34], collectively enhanced the strength and acid resistance of RPC-FA in the 28-day-cured samples.

4. Conclusions

1. The use of supplementary cementitious materials (fly ash or GGBS) improved the workability and flow characteristics of the fresh RPC mixtures.
2. Replacing 25% of the cement with supplementary cementitious materials such as fly ash or GGBS enhances acid resistance in reactive powder concrete.
3. In RPC specimens cured for 3 days, RPC-S exhibited superior acid resistance and showed minimal detrimental effects when compared to RPC-C and RPC-FA.
4. RPC-FA specimens exhibited weaker acid resistance at an early age compared to RPC-S. However, this resistance improved over time, curing for 28 days.
5. Both RPC-FA and RPC-S exhibited lower weight loss compared to RPC-C, indicating improved acid resistance and durability for the group of specimens cured for 28 days.
6. The ultrasonic pulse velocity results showed that after 56 days of immersing in 3% sulfuric acid, RPC-FA exhibited the highest velocity among the 28-day-cured specimens, followed by RPC-S among the 3-day-cured specimens. This indicates excellent concrete quality for both RPC-FA and RPC-S, as higher velocity indicates greater resistance to acid attack.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Mohammed Saad: Conducted the experimental work for the research and obtained the results.

Eman Kh. Ibrahim: Supervised the study, made necessary revisions to the research, analyzed the results, and drew conclusions.

Both authors discussed the results and contributed to the final manuscript.

References

[1] M. M. Salman, Q. J. Frayyeh, and L. A. Zghair, "Stress –Strain Diagram Of Self-Consolidating Concrete Subjected To Chemical Attack," *Journal of Engineering and Sustainable Development*, vol. 26, no. 5, pp. 105–114, Sep. 2022, doi: https://doi.org/10.31272/jeasd.26.5.10

[2] F. Yang, Y. Zhao, T. Wang, Y. Song, G. Jiang, and M. Wu, "Advances on Corrosion-Resistant Concrete for Sewers," *Engineering Materials*, pp. 185–218, 2023, doi: https://doi.org/10.1007/978-3-031-29941-4_9

[3] P. Richard and M. Cheyrezy, "Composition of Reactive Powder Concretes," *Cement and Concrete Research*, vol. 25, no. 7, pp. 1501–1511, Oct. 1995, doi: https://doi.org/10.1016/0008-8846(95)00144-2

[4] Supriya, R. Chaudhury, U. Sharma, P. C. Thapliyal, and L. P. Singh, "Low-CO2 Emission Strategies to Achieve Net Zero Target in Cement Sector," *Journal of Cleaner Production*, vol. 417, p. 137466, Sep. 2023, doi: https://doi.org/10.1016/j.jclepro.2023.137466

[5] S. Barbhuiya and D. Kumala, "Behaviour of a Sustainable Concrete in Acidic Environment," *Sustainability*, vol. 9, no. 9, p. 1556, Sep. 2017, doi: https://doi.org/10.3390/su9091556

[6] K. J. Rao, K. Keerthi, and S. Vasam, "Acid Resistance of Quaternary Blended Recycled Aggregate Concrete," *Case Studies in Construction Materials*, vol. 8, pp. 423–433, Jun. 2018, doi: https://doi.org/10.1016/j.cscm.2018.03.005

[7] A. L. T. Torres, L. M. S. de Souza, M. I. P. da Silva, and F. de Andrade Silva, "Concrete Degradation Mechanisms by Sulfuric Acid Attack," *Magazine of Concrete Research*, vol. 71, no. 7, pp. 349–361, Apr. 2019, doi: https://doi.org/10.1680/jmacr.18.00194

[8] Y. Aygörmez and O. Canpolat, "Long-term Sulfuric and Hydrochloric Acid Resistance of Silica Fume and Colemanite Waste Reinforced metakaolin-based Geopolymers," *Revista de la construcción*, vol. 20, no. 2, pp. 291–

307, Aug. 2021, doi: https://doi.org/10.7764/rdlc.20.2.291

[9] A. A. Dhundasi, R. B. Khadiranaikar, A. A. Momin, and K. Motagi, "An Experimental Investigation on Durability Properties of Reactive Powder Concrete," *International Journal of Engineering*, vol. 35, no. 2, pp. 327–336, 2022, doi: https://doi.org/10.5829/ije.2022.35.02b.08

[10] F. Z. Youssari, O. Taleb, and A. S. Benosman, "Towards Understanding the Behavior of fiber-reinforced Concrete in Aggressive environments: Acid Attacks and Leaching," *Construction and Building Materials*, vol. 368, p. 130444, Mar. 2023, doi: https://doi.org/10.1016/j.conbuildmat.2023.130444.

[11] A. Arjomandi *et al.*, "The Effect of Sulfuric Acid Attack on Mechanical Properties of Steel fiber-reinforced Concrete Containing Waste Nylon aggregates: Experiments and RSM-based Optimization," *Journal of Building Engineering*, vol. 64, pp. 105500–105500, Apr. 2023, doi: https://doi.org/10.1016/j.jobe.2022.105500

[12] M. Shariati *et al.*, "Sulfuric Acid Resistance of Concrete Containing Coal Waste as a Partial Substitute for Fine and Coarse Aggregates," *Fuel*, vol. 348, pp. 128311–128311, May 2023, doi: https://doi.org/10.1016/j.fuel.2023.128311

[13] I.Q.S: Iraqi Standards Specifications No.5, "Iraqi Standard Specification, Portland cement". 2019

[14] ASTM International. C1240-20, "Standard Specification for Silica Fume Used in Cementitious Mixtures;" *ASTM International*: West Conshohocken, PA, USA. 2020.

[15] ASTM International C618-19, "Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM International. 2019, doi: https://doi.org/10.1520/c0618-12a

[16] BS EN 15167-1. "Ground Granulated Blast Furnace Slag for Use in Concrete, Mortar and Grout. Part 1: Definitions, Specifications, and Conformity Criteria*," BSI Standard Limited: London, UK*. 2006.

[17] P. W. Leung and H. D. Wong, "Final Report on Durability and Strength Development of Ground Granulated Blast Furnace Slag concrete. ," *Geotechnical Engineering office, Civil Engineering*, 2010.

[18] ASTM, C., 1437, "Standard test method for flow of hydraulic cement mortar. West Conshohocken, PA" *American Society for Testing and Materials (ASTM) International.* 2020.

[19] BS EN 12390-3, "Testing Hardened Concrete. Part 3: Compressive Strength of Test Specimens". *BSI Standard Limited:* London, UK. 2019.

[20] ASTM C496/C496M-17 "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens" *American Society for Testing and Materials International*: West Conshohocken, PA, USA, pp. 5. 2017.

[21] ASTM C597 - 16, "Standard Test Method for Pulse Velocity Through Concrete", *American Society of Testing and Materials*. pp. 1–4. 2016

[22] No, T.C.S., "Guidebook on non-destructive testing of concrete structures". *Training Course Series*. 2002.

[23] M. A. M. Johari, J. J. Brooks, S. Kabir, and P. Rivard, "Influence of Supplementary Cementitious Materials on Engineering Properties of High Strength Concrete," *Construction and Building Materials*, vol. 25, no. 5, pp. 2639–2648, May 2011, doi: https://doi.org/10.1016/j.conbuildmat.2010.12.013

[24] R. C. Joshi and R. Lohita, "98/00323 Fly Ash in concrete: Production, Properties and Uses," *Fuel and Energy Abstracts*, vol. 39, no. 1, p. 26, Jan. 1998, doi: https://doi.org/10.1016/0140-6701(98)94358-2

[25] A. Aghaeipour and M. Madhkhan, "Abstract of: Ground Granulated Blast Furnace Slag as a Cementitious Constituent in Concrete and Mortar," *ACI Materials Journal*, vol. 92, no. 3, 1995, doi: https://doi.org/10.14359/1125

[26] H. SONG and V. SARASWATHY, "Studies on the Corrosion Resistance of Reinforced Steel in Concrete with Ground Granulated blast-furnace slag—An Overview," *Journal of Hazardous Materials*, vol. 138, no. 2, pp. 226–233, Nov. 2006, doi: https://doi.org/10.1016/j.jhazmat.2006.07.022

[27] R. A. T. Cahyani and Y. Rusdianto, "Concrete Performance with Ground Granulated Blast Furnace Slag as Supplementary Cementitious Materials," *IOP Conference Series: Materials Science and Engineering*, vol. 771, p. 012062, Mar. 2020, doi: https://doi.org/10.1088/1757-899x/771/1/012062

[28] M. Kewalramani and A. Khartabil, "Porosity Evaluation of Concrete Containing Supplementary Cementitious Materials for Durability Assessment through Volume of Permeable Voids and Water Immersion Conditions," *Buildings*, vol. 11, no. 9, p. 378, Aug. 2021, doi: https://doi.org/10.3390/buildings11090378

[29] P. Munjal, K. K. Hau, and C. C. Hon Arthur, "Effect of GGBS and Curing Conditions on Strength and Microstructure Properties of Oil Well Cement Slurry," *Journal of Building Engineering*, vol. 40, p. 102331, Aug. 2021, doi: https://doi.org/10.1016/j.jobe.2021.102331

[30] V. M. Malhotra, M. H. Zhang, P. H. Read, and J. Ryell, "Long-Term Mechanical Properties and Durability Characteristics of High-Strength/High-Performance Concrete Incorporating Supplementary Cementing Materials under Outdoor Exposure Conditions," *ACI Materials Journal*, vol. 97, no. 5, 2000, doi: https://doi.org/10.14359/9284

[31] J. Sun, X. Shen, G. Tan, and J. E. Tanner, "Compressive Strength and Hydration Characteristics of high-volume Fly Ash Concrete Prepared from Fly Ash," *Journal of Thermal Analysis and Calorimetry*, vol. 136, no. 2, pp. 565–580, Aug. 2018, doi: https://doi.org/10.1007/s10973-018-7578-z.

[32] C. Herath, C. Gunasekara, D. W. Law, and S. Setunge, "Performance of High Volume Fly Ash Concrete Incorporating additives: a Systematic Literature Review," *Construction and Building Materials*, vol. 258, p. 120606, Oct. 2020, doi: https://doi.org/10.1016/j.conbuildmat.2020.120606

[33] G. Li and X. Zhao, "Properties of Concrete Incorporating Fly Ash and Ground Granulated blast-furnace Slag," *Cement and Concrete Composites*, vol. 25, no. 3, pp. 293–299, Apr. 2003, doi: https://doi.org/10.1016/s0958-9465(02)00058-6

[34] S. S. S. A. Nedunuri, S. G. Sertse, and S. Muhammad, "Microstructural Study of Portland Cement Partially Replaced with Fly ash, Ground Granulated Blast Furnace Slag and Silica Fume as Determined by Pozzolanic Activity," *Construction and Building Materials*, vol. 238, p. 117561, Mar. 2020, doi: https://doi.org/10.1016/j.conbuildmat.2019.117561