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Ph.D. in Civil Engineering

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Title of Paper**: Durability performances of geopolymer concrete incorporated recycled plastic aggregate modified with nanoparticles**

Durability performances of geopolymer concrete incorporated recycled plastic aggregate modified with nanoparticles

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Abstract

The re-use of plastics for the production of geopolymer concrete is a significant step towards reducing plastic waste and mitigating the environmental impact of construction materials. Plastics have become a major environmental issue, and finding ways to recycle them is essential for a sustainable future. However, incorporating recycled plastic aggregates (RPAs) can adversely affect several properties of concrete. Previous studies have attempted to mitigate this negative impact by applying surface treatments to the RPAs. Research regarding the improvement of RPA geopolymer concrete (GPC) properties by the addition of nano-silica particles (NS) is scarce. Therefore, the current study aims to experimentally investigate the properties of the GPC-incorporated RPAs modified with NS. The experimental program contained seventeen different mixtures which were subdivided into three stages. In the first stage the GGBFS was replaced by 1%, 2%, 3%, and 4% NS particles, while, in the second stage, the natural fine aggregate was replaced by RPAs at six volume fractions (5%, 10%, 20%, 30%, 40%, and 50%). The effect of elevated temperature at 300 °C, 600 °C and 900 °C were also investigated. The durability performance in terms of water absorption, acid attack, electrical resistivity, chloride permeability, and bulk electrical conductivity were also extensively studied. The results indicated that, the addition of NS particles substantially improved the performance of GPC mixtures in the first stage, and the optimum percentage was 3% of NS particles. While in the second stage, the durability properties of GPC mixtures were systematically degraded due to the incorporation of RPAs. Finally, the addition of an optimum percentage of NS particles can significantly restore most properties of RPAGPCs in the third stage which were degraded due to the addition of RPAs. This technique can help the construction industry to safely use the RPAs in the GPC mixtures without concern about their negative impact on concrete performance.

Keywords:

Recycled plastic aggregates; Nanosilica particles; Elevated temperature resistance; Durability performances; Electrical conductivity.

1. Introduction

Due to growing environmental concerns, it has become necessary to create and advance novel binding construction materials that can replace traditional Portland cement. Cement, aggregates, and water are the primary components of traditional concrete composites, which are extensively utilized in constructing various engineering projects. However, these materials have a detrimental impact on the environment, contributing to issues such as CO_2 emissions and the depletion of natural resources (Habert et al., 2020). Producing cement involves heating around 2.8 tons of raw materials, including powdered limestone and shale, to create a single ton of cement (Guo et al., 2010). As a result, the cement industry is responsible for more than 5% of global air pollution (Gartner, 2004).

At present, Portland cement is the principal binding agent used to manufacture concrete composites There have been endeavours to produce concrete composites utilizing an alternative binding agent, such as geopolymer materials. These materials were initially invented by French scientist Davidovits in 1970, and have been researched for their feasibility in construction ever since (Ahmed et al., 2022a). Due to the utilization of diverse waste ashes in their composition proportions, these innovative substances reduce CO_2 emissions by 70% in comparison to a typical cement binder (Weil et al., 2009).

Geopolymer concrete is a relatively new type of cementitious material that has shown potential for a variety of applications due to its excellent mechanical properties, durability, and sustainability. Geopolymers are produced through the use of alkaline activation on various source materials that are rich in aluminum and silicate, such as ground granulated blast furnace slag (GGBFS) and fly ash (Davidovits, 2015). To make geopolymer concrete, source binder materials, aggregates, and alkaline solution are blended together to create the concrete ingredients. The process of creating the concrete involves polymerization, which occurs when the source binder materials and alkaline solutions react with each other (Ahmed et al., 2021a). The property of geopolymer concrete is influenced by variety of parameters, such as, the ratio of sodium silicate to sodium hydroxide, the ratio of alkaline solution to source binder materials, curing condition, extra water and superplasticizer content, the molarity of sodium hydroxide, and the aggregate type and quality. (Mohammed et al., 2021). Scholars employed heat-curing regimes to cure geopolymer concrete specimens to speed up the polymerization process and obtain geopolymers with the desired mechanical and physical properties. This method of curing restricts the usage of geopolymer concrete in site engineering projects and limits the use of geopolymer concrete in precast concrete elements (Hassan et al., 2019). To overcome these issues, nanoparticles (NPs), one of the methods, have been employed to produce geopolymers with ambient curing conditions (Ahmed et al., 2022b). Nanotechnology is a new revolutionary subject in civil engineering still in its early stages. Nanomaterials of various types provide significant advantages over other additions to GPC composites, including superior mechanical characteristics and long-term durability (Sharif, 2021). Currently, Nano silica (NS) is of interests of many building industries due to its extraordinarily high surface area which significantly improves characteristics of concrete by providing extra C-S-H gels in the pozzolanic reaction and acting as pore nano-fillers (Faraj et al., 2022).

The utilization of waste plastics in traditional concrete has been extensively studied, but the incorporation of recycled plastic aggregates (RPAs) into geopolymer concrete (GPC) remains a relatively unexplored area of research. Previous studies have indicated that adding RPAs to GPC can have a detrimental impact on its quality, which has led researchers to experiment with various approaches, such as surface treatment of the aggregates, to mitigate this effect. However, despite the numerous investigations, there is still a scarcity of research on enhancing the properties of RPA geopolymer concrete through the incorporation of nano-silica particles. Hence, this study aims to explore the potential of using NS to enhance various attributes of geopolymer concrete while simultaneously incorporating RPAs. The results of this study have significant implications for the construction industry as they provide new insights into the effects of NS and RPAs on GGBFS-based geopolymer concrete. This information can assist in the development of more sustainable and long-lasting construction materials, which is essential in today's environmentally conscious world. Moreover, the application of nano-silica particles in geopolymer concrete with recycled plastic aggregates could provide a practical solution to the problem of plastic waste in the construction industry. By using RPAs and nano-silica particles in GPC, waste plastics can be diverted from landfills and repurposed in a useful and sustainable manner.

2. Experimental program and Methodology

2.1. Materials

Figure 1a displays that GGBFS served as the primary binder material for producing geopolymer concrete mixtures. The particle size of GGBFS ranges from 10 µm. Additionally, the geopolymer concrete mixtures employed a consistent percentage of around 10% of the total binder content of silica-fume, as illustrated in Figure 1b. The silica-fume (SF), which has rounded particles that measure between 500 nm and less in size. In addition, hydrophilic NS particles in powdered form were procured from LUOYANG company in China, as demonstrated in Figure 1c. The tiny nanoparticles (NPs) of NS, which fall in the range of 30 nm, can significantly improve the performance of GPC mixtures. A commercially available superplasticizer called Hyperplast PC900 from a DCP company with a slump retention capacity was used. This superplasticizer adheres to ASTM C494, TYPE G standards and has a specific gravity of 1.12 g/cm^3 and a pH range between 5 and 7.

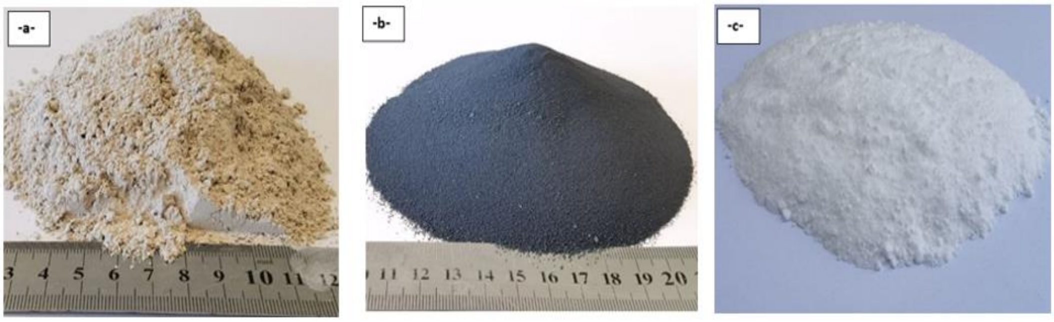


Fig.1: Materials used in this study, (a): GGBFS; (b): SF; (c): NS; (d): RPA

In addition, a mix of well-graded crushed coarse and natural river fine aggregates were utilized, which had a specific gravity of 2.69. The coarse aggregate had a size of 12.5 mm and a water absorption rate of 1.37%, whereas the fine aggregate had a water absorption rate of 1.73%. The gradation for both types of aggregates (coarse and fine) is shown in Figures 2a and 2b, respectively. For the alkaline solution, a combination of 12M sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions were used as the liquid alkaline for geopolymer concrete mixtures. These solutions were obtained from the Malbray chemical factory in Erbil, Kurdistan Region, Iraq (36°10'03.6"N, 44°00'41.1"E). The NaOH was in pellet form with a purity of 98%, while the sodium silicate was in liquid form and consisted of 37.5% SiO2, 16.5% Na_2O, and 46% H_2O. The gravity of sodium silicate was 1.34, and that of sodium hydroxide was 1.5. Table 2 provides details on the chemical compositions of both NaOH and Na_2SiO_3.

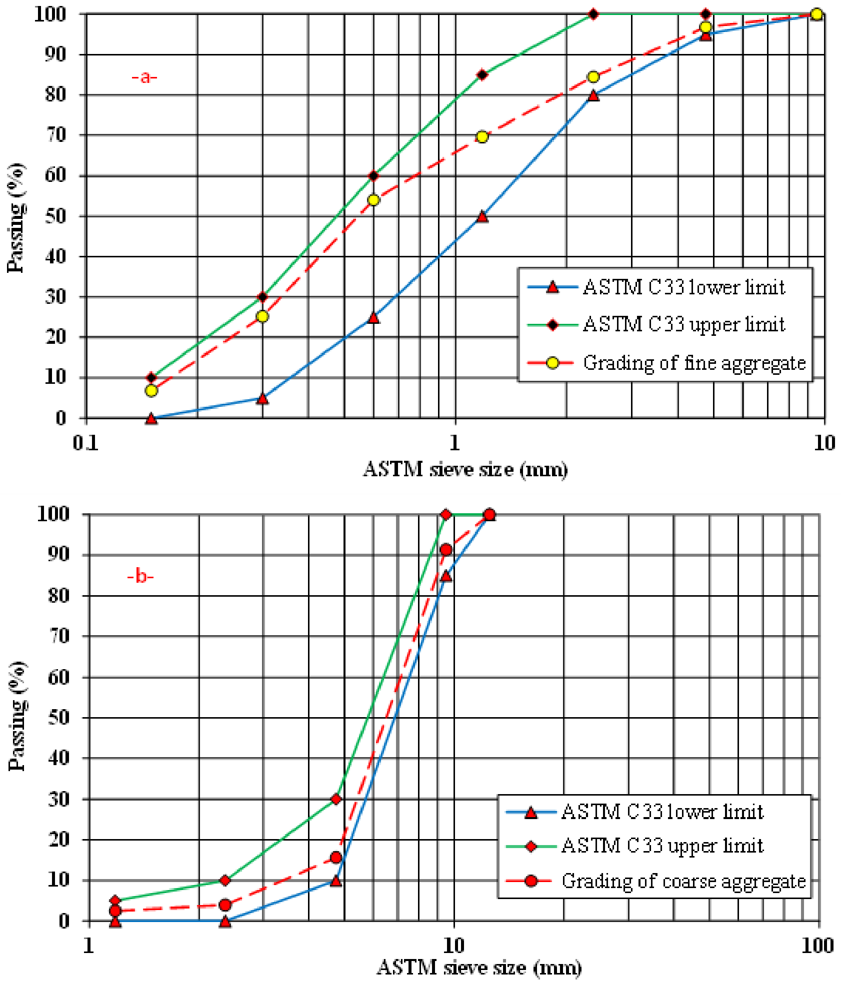


Fig.2: Sieve analysis aggregates; (a): fine aggregate; (b): coarse aggregate

2.2. Mix proportions

In total, 17 different mixtures of geopolymer concrete were prepared by varying the dosages of nano-silica (NS) and recycled plastic aggregates (RPA). The mix design procedures followed the guidelines provided by Reddy et al. (2018) and Li et al. (2019) to ensure that the concrete proportions were balanced for workability, strength, durability, density, and appearance criteria while also being economical. The experiment was conducted in three stages.

In the first stage, five mixtures were prepared, including a control mixture without any replacements. Four different percentages of NS particles were used to replace the total binder content, including 1%, 2%, 3%, and 4% by weight. Each mixture was named according to its composition, where P0NS0 referred to the control mixture (G1) with 0% RPAs and 0% NS particles, and P0NS1 referred to (G2) with 0% RPAs and 1% NS particles. The same naming sequence was applied to other mixtures in the first stage.

The second stage involved replacing the fine natural aggregate with six different percentages of RPA by volume, namely 5, 10, 20, 30, 40, and 50%. Mixtures were named similarly to the first stage, where P5NS0 referred to (G6) with 5% RPAs and 0% NS particles. Replacement percentages higher than 50% were not feasible due to poor fresh behaviour of the geopolymer concrete and significant segregation.

In the final stage, an optimum percentage of NS particles found in the first stage was used for all mixtures that incorporated RPAs. Six mixtures with different percentages of RPAs and 3% NS particles were cast. The aim of this stage was to determine the effect of incorporating the optimum percentage of NS particles on the RPAGPC mixtures. The same naming sequence was used as in the previous stages. Table 1 provides details of the mix proportions for all 17 mixtures.

Table 1: GPC mix proportions in kg/m^3

Stages	Mix No.	Mix ID.	GGBFS	SF	NS	SH	SS	EW	SP	FA	CA	RPA
First stage	G1	P0NS0	400	50	0	64.3	160.7	24.75	9.45	612.28	1104.27	0
	G2	P0NS1	395.5	50	4.5	64.3	160.7	24.75	9.45	607.55	1095.72	0
	G3	P0NS2	391	50	9	64.3	160.7	24.75	9.45	602.82	1087.2	0
	G4	P0NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	598.10	1078.67	0
	G5	P0NS4	382	50	18	64.3	160.7	24.75	9.45	593.37	1070.14	0
Second stage	G6	P5NS0	400	50	0	64.3	160.7	24.75	9.45	581.66	1104.25	9.95
	G7	P10NS0	400	50	0	64.3	160.7	24.75	9.45	551.05	1104.25	19.89
	G8	P20NS0	400	50	0	64.3	160.7	24.75	9.45	489.82	1104.25	39.79
	G9	P30NS0	400	50	0	64.3	160.7	24.75	9.45	428.6	1104.25	59.68
	G10	P40NS0	400	50	0	64.3	160.7	24.75	9.45	367.37	1104.25	79.57
	G11	P50NS0	400	50	0	64.3	160.7	24.75	9.45	306.14	1104.25	99.47
Third stage	G12	P5NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	568.19	1078.67	9.72
	G13	P10NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	538.29	1078.67	19.43
	G14	P20NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	478.48	1078.67	38.87
	G15	P30NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	418.67	1078.67	58.30
	G16	P40NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	358.86	1078.67	77.73
	G17	P50NS3	386.5	50	13.5	64.3	160.7	24.75	9.45	299.05	1078.67	97.16

2.3. Mixing and casting

The importance of mixing sequence and duration in producing GPC led to following a batching procedure and constant mixing to ensure uniformity and homogeneity in all mixtures. In the first step, granular materials such as RPAs, coarse and fine aggregates were put into a power-driven revolving pan mixer and mixed for 0.5 minutes to achieve homogeneity. In the second step, powdered materials such as GGBFS, silica fume, and/or NS particles were added to the mixer and mixed with aggregates for almost 1 minute. In the final step, the alkaline solution, which had been prepared the previous day, and a mixture of extra water and superplasticizer were slowly poured into the mixer for 3 minutes. After the mixing procedure was complete, several samples were cast in the required molds with lubricating surfaces to test the GPC mixes' mechanical properties. A vibrating table was used to make the GPC denser and remove air bubbles when poured into the molds. The specimens were removed from the mold after 24 hours and kept in the lab at 23 ± 2 °C until they were cured and ready for testing.

2.4. Test setup

In order to determine the workability of the geopolymer concrete mixes while still in the fresh state, a slump test was performed following the guidelines of ASTM C143. Additionally, to determine the residual compressive strength of the GPC mixes under different conditions, cylindrical samples measuring 100 x 200 mm were tested in accordance with ASTM C39, using a universal testing compression machine with a capacity of 3000 kN. This test was conducted on three samples from each GPC mix at 28, 90, and 180 days to determine the residual compressive strength after exposure to acidic environments, and at 28 days to examine elevated temperature behaviours. The specimens were loaded at a stress rate of 0.25 MPa/s, and the compressive strength was calculated by averaging the results from the three tested samples at each testing age. The specimens' surfaces were capped using sulphur mortar following the guidelines of ASTM C617. Table 2 presents a comprehensive list of all the other tests conducted on the geopolymer concrete mixes for this study, along with the standard test methods applied.

Table 2: Tests and standard test methods followed in this study

NO.	Tests	Standard test methods	Test date (Days)
1	Water absorption	ASTM C642	28 & 90
2	Resistance to acid environment	ASTM C1898	90 & 180
3	Rapid chloride permeability	ASTM C1202	90

3. Results and discussions

3.1. Strength development at different curing conditions

Compressive strength is one of the essential mechanical characteristics of concrete structures, and it usually provides a general performance regarding the concrete's quality. In order to evaluate the residual compressive strength of GPC mixtures after being exposed to high temperature, the normal compressive strength was compared by subjecting them to 28-day ambient curing conditions. On the other hand, to determine how GPC mixtures are affected by acidic environments, the 28-day standard water curing conditions were used.

Overall, the compressive strength of all GPC specimens was observed to be significantly higher in water curing conditions compared to the ambient curing environments, as shown in Figure 3. According to the data shown in Figure 3. Adding NS to the GPC mixtures has a stronger and more active effect in water-curing circumstances than in ambient curing conditions. For example, at NS loading rates of 1, 2, 3, and 4%, compressive strength was improved by 14.7%, 23.9%, 31.3%, and 25.5%, respectively, for water curing conditions; however, these improvements were reduced to 9.4%, 14.4%, 20.5%, and 12.1%, respectively, for ambient curing conditions with the same order. In the water curing conditions, partial replacement of fine aggregate by 5, 10, 20, 30, 40, and 50% RPA results in compressive strength losses of 3.13%, 6.51%, 13.5%, 18.8%, 28.9%, and 44.1%, respectively, compared to the control GPC samples, while these results are further reduced to 4.7%, 7.38%, 14.8%, 20.8%, 29.2%, and 44.6% in the ambient curing conditions for the same order already stated. This finding supported the idea that the hydration process accelerated in the presence of water, leading to a greater number of products being formed as a result of chemical reactions between water, GGBFS, silica fume, and NS particles, which in turn improved the compressive strength of the GPC mixtures (Kumar et al., 2010; Puligilla and Mondal, 2013); on the other hand, it is possible to assert that the hydration process would be active in the presence of water; as a result, both the hydration and geopolymerization mechanisms create their byproducts such as C–S–H, N–A–S–H, and C–A–S–H gels, increasing the GPC's strength.

Finally, at ambient curing conditions, it was observed that adding 3% of NS for GPC mixtures with natural sand replacement levels of 5% and 10% by RPA, improved the compressive strength by 14.8% and 11.41%, correspondingly, compared to the control GPC mixtures. This enhancement in the compressive strength was comparable to 20.42% and 20.29% relative to their reference mixes without 3% of NS. While the percentage of sand replaced with RPAs continues to rise, the compressive strength value decreases by 0.34%, 9.06%, 19.13%, and 38.59% for 20, 30, 40, and 50% of RPA contents, respectively, in comparison to the control GPC mixture. Additionally, compared to the identical mixes without any dosages of NS, it was discovered that these outcomes were improved by 16.93%, 14.83%, 14.22, and 10.91%. However, these improvements were higher for the standard water curing conditions.

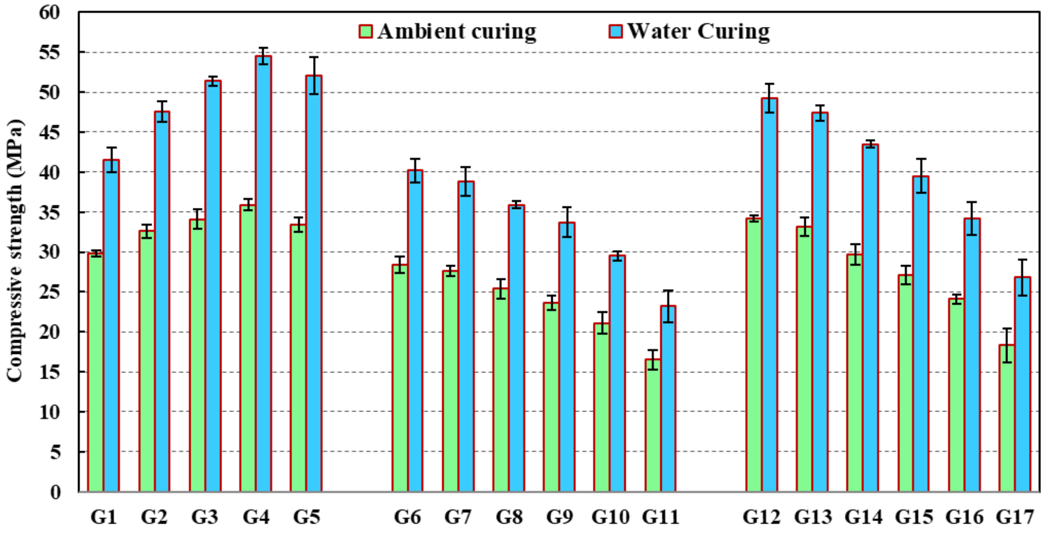


Fig.5: Effects of curing conditions on the compressive strength of GPC mixtures with and without NS and RPA at the age of 28 days

3.2. Durability properties

3.2.1. Water absorption

The results of the water absorption at 28 and 90-day ages are presented in Figure 4. It can be seen that the water absorption capacity of the GGBFS-based geopolymer concrete decreased as the dosages of NS increased up to 2% and then slightly increased. Because every type of NP acts as a nanofiller, reducing the number of micropores within the geopolymer matrix; consequently, adding NPs reduces the water absorption rate of geopolymer composites up to a certain dosage. However, with agglomeration and poor dispersion of NPs, dosages greater than the optimal content were ineffective at enhancing water absorption, as with mechanical properties (Ahmed et al., 2022a).

As depicted in Figure 4, the amount of water absorption significantly improved by 18.71%, 32.16%, 31.58%, and 26.02% at 1, 2, 3, and 4% of NS, respectively, relative to the zero percent of NS content in the control specimens at the age of 28 days. On the other hand, this enhancement in reducing water absorption slightly rose at 90 days due to further hydration of reactive nano-silica particles. For example, the average water absorption for the reference specimens was 3.37% and then declined to 2.69%, 2.09%, 2.14%, and 2.36% at the loading rate of NS content of 1, 2, 3, and 4%. These reductions in the water absorption were comparable to the 20.18%, 37.98%, 36.5%, and 29.97% improvements in the geopolymer concrete mixtures, which contain 1, 2, 3, and 4% of NS, correspondingly. Similar results of improving water absorption capacity have been recorded in the literature (Ekinci et al., 2019; Nuaklong et al., 2018; Nuaklong et al., 2020); for instance, Nuaklong et al. (2020) reported that the addition of different dosages of NS improved the water absorption capacity of high calcium fly ash-based geopolymer concrete composites by 55.3%, 47.6%, and 34% at 1, 2, and 3% of NS content, compared to their control mix. Moreover, Sun et al. (2020) observed that the water absorption of metakaolin-based geopolymer mortar was decreased by 13%, 15%, and 25% when 1, 2, and 3% NS.

However, Etemadi et al. (2020) and Angelin Lincy and Velkennedy (2020) claimed that adding NS to geopolymer concrete slightly improved water absorption.

The second part of this investigation has been performed to demonstrate the impact of varying RPA dosages as a natural fine aggregate replacement on the water absorption of GPC mixes. The influence of RPA contents on the average water absorption of geopolymer concrete is shown in Figure 4. The average water absorption at 28 days for GPC mixtures without RPAs was 3.42%, but as the sand replacement percentage grew, this value increased as well, reaching 4.61% for GPC containing 50% RPA as fine aggregate, which is 34.8% lower than the reference GPC specimen. Compared to the control GPC samples, the water absorptions increased by 7.31%, 11.7%, 18.42%, and 23.10% for the other RPA dosages of 10%, 20%, 30%, and 40%. At 90 days, these roses in the water absorption values were slightly reduced due to the ongoing geopolymerization process compared to the curing ages of twenty-eight days. For instance, water absorption value increases by 3.26% when 5% of RPA is added to the GPC mixture as a natural substitute for fine aggregates, compared to the control GPC specimens. Also, in GPC samples with 10 and 20% of RPAs, respectively, the near values of the increase in the water absorption values of about 5.93% and 8.61% were observed. However, compared to the virgin GPC mixture, the water absorption rose for the other natural sand replacement level with RPAs by 16.02%, 19.58%, and 29.60% at 30, 40, and 30% doses of RPAs, respectively. These results in the ascent of water absorption values with increasing the amount of RPA contents were attributed to the fact that adding RPA caused a more porous structure at all mixtures; the more porous structure of GPC mixtures caused more water absorption values; on the other hand, plastic, and natural aggregates did not combine mix sufficiently in the geopolymer concrete matrix, and thus the resultant concrete became porous, and water absorption was increased (Akçaözogˇlu and Ulu, 2014; Gu and Ozbakkaloglu, 2016). Although lack of research has been done in this area, similar results have also been published in the literature. Akçaözogˇlu and Ulu (2014) investigated the effects of adding recycled PET granules as natural fine aggregate on the different engineering properties of blended GGBFS/metakaolin-based geopolymer concrete was found that adding PET granules increased the amount of water absorption relative to their control GPC mixtures. In the same context, Wongkvanklom et al. (2019) showed that adding various dosages of recycled plastic beads as a natural sand replacement to lightweight geopolymer concrete greatly increases the water absorption values. Water absorption, for example, was 5.5% for the control specimen and was reduced or increased check to 8.3%, 8.1%, 11.2%, and 12.5% for loading rates of recycled plastic aggregate percentages of 25%, 50%, 75%, and 100%, respectively.

Figure 4 depicts the results of experimental laboratory work for various GPC mixtures; the right side of Figure 4 depicts those GPC mixtures (G12 to G17) containing varying dosages of RPA with the optimum dosages of NS. At the age of 28 days, the value of water absorption for the GPC mixtures, which contain 5, 10, 20, 30, 40, and 50% of RPAs and 3% of NS, were 2.85%, 2.98%, 3.45%, 3.74%, 3.95%, and 4.36%, respectively; while the water absorption for the control GPC mixture was 3.42%. It can be seen that the addition of NS to the GPC mixtures significantly improved the water absorption capacity of the GPC mixtures; for example, the addition of 3% of NS decreased the water absorption by 16.67% and 12.87% for those GPC mixtures that incorporate 5% and 10% of RPA dosages, respectively, compared to the control GPC samples without any dosages of NS and RPAs. However, for the other GPC mixtures that contain 20%, 30%, 40%, and 50% of RPAs, the water absorption values were increased by 0.88%, 9.36%, 15.5%, and 27.49%, correspondingly. In other words, when these results were compared to their reference mixtures, it was discovered that adding 3% NS improves the water absorption capacity of the mixtures by 9.68, 7.65, 6.18, and 5.42. These results were attributed to the fact that adding NS to the mixtures decreased the nano-voids and pores within the geopolymer concrete microstructure and produced in the geopolymer concrete microstructure and produced more extra gels during the polymerization process with the presence of NS.

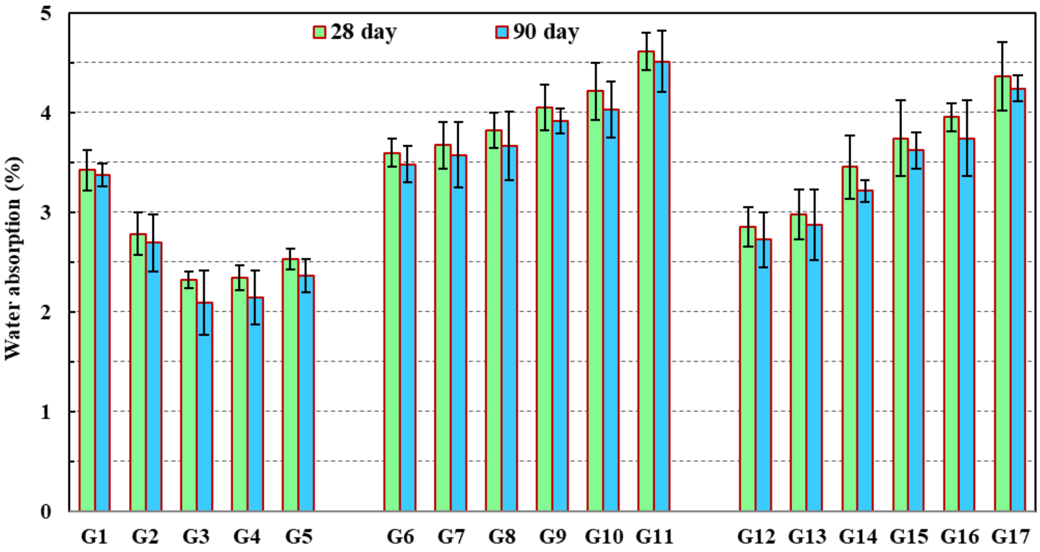


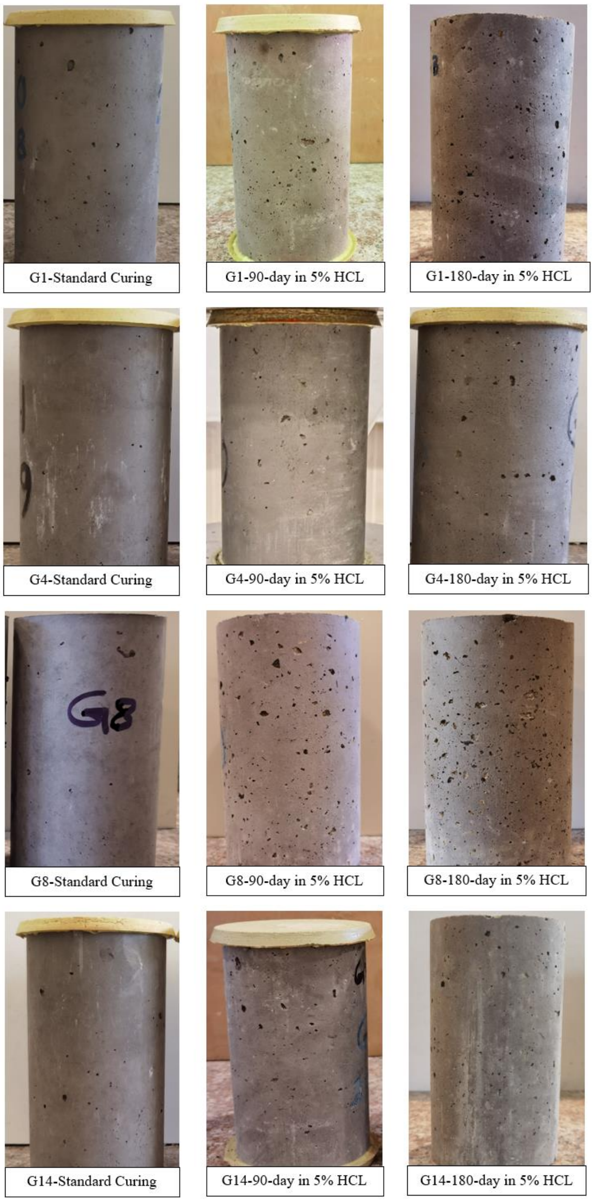
Fig.4: Water absorption of GPC mixtures with and without NS and RPA

3.2.2.Resistance to acid environment

3.2.2.1. Visual appearance

According to Ariffin et al. (2013), Deb et al. (2016), and Çevik et al. (2018), the 28-day compressive strength of each geopolymer mix before acid solution exposure is used as a benchmark to compute the mass and strength loss after each exposure periods of 90, and 180 days. The visual characteristics of GPC specimens under 5% hydrochloric acid solutions for 90 and 180 days are shown in Figure 5. In general, it is seen that all the geopolymer concrete specimens exhibited slight surface erosion and roughness. The erosion quantity increased as exposure duration increased from three to six months, and the percentages of RPAs increased. Specimens of geopolymer concrete made from GGBFS that lacked nano-silica exhibited somewhat higher surface degradation (G1, G8, G10) than those that contained nano-silica (G4, G14, G16). Consequently, the beneficial effect of nano-silica on the durability performance of geopolymer concrete can be detected even in the long term.

Nonetheless, slight surface softening was observed on all specimens compared to unexposed specimens. On the other hand, no significant difference in appearance was observed, and the surface color was slightly changed from the characteristic grey to light grey. These results demonstrated that the geopolymer concrete specimens modified with NS g greatly resist the acidic environment. However, the addition of RPAs to the GPC mixtures adversely affects the acid resistance of GPC mixtures. Similar results of the slight change in the appearance, surface erosion, and roughness of geopolymer concrete incorporated in different dosages of NS have been reported in previous studies (Çevik et al., 2018; Nuaklong et al., 2018).



G1-Standard Curing
G1-90-day in 5% HCL
G1-180-day in 5% HCL
G4-Standard Curing
G4-90-day in 5% HCL
G4-180-day in 5% HCL
G8-Standard Curing
G8-90-day in 5% HCL
G8-180-day in 5% HCL
G14-Standard Curing
G14-90-day in 5% HCL
G14-180-day in 5% HCL

Fig.5: Visual appearance of different GPC specimens after being exposed to an acidic environment

3.2.2.2. Weight loss

The results of the weight loss of GPC modified with various dosages of NS at different curing ages are presented in Figure 6. It is clearly seen that the weight loss of geopolymer samples decreased as the dosages of NS increased. For instance, the percentages of weight loss after immersing the GPC samples for about 90 days in an acidic environment were 3.12%, 2.84, 2.53, 2.15, and 2.28%, at 0, 1, 2, 3, and 4% of NS dosages, respectively. The amount of weight loss improvement was 8.97%, 18.91%, 31.09%, and 26.92% at 1, 2, 3, and 4% of NS contents, respectively, compared to the control GPC mixture. Overall, the weight loss of geopolymer concrete specimens with and without NS was revealed to the alkali and some material dissolution from concretes into the acidic environment (Thokchom, 2014). The depolymerization of aluminosilicate polymers in acidic media was the cause of the decrease in the weight and strength of geopolymer concrete in acidic environments (Bakharev, 2005). Furthermore, after soaking the geopolymer concrete specimens for about 180 days in the same previous environment, the percent of weight loss was recorded as 4.21%, 3.95%, 3.64%, 3.25%, and 3.37% for the previous mixtures' sequences. Here the role of adding NS to the geopolymer concrete mixtures clearly could be seen, as the presence of NS significantly reduced the weight loss by 6.18%, 13.54%, 22.8%, and 19.95%, in the geopolymer mixtures with 1, 2, 3, and 4% of NS inclusion, correspondingly, in relative to the virgin GPC specimens. These results were argued to the NPs' pore-refining process, which prevents the passage of aggressive components into the deeper layers of the hydrated gel structure, as well as the NPs' production of a denser structure that is resistant to acid degradation (Belkowitz et al., 2015). On the other hand, NS will increase the proportion of soluble silica in the geopolymer mixture, resulting in a denser layer and decreasing the damage to the aluminosilicate structure produced by the loss of each aluminum atom under acid attack (Hartman and Fogler, 2007). Similar results for improving the weight loss of geopolymer concrete have been observed in the literature; for example, tests by Patel et al. (2015) demonstrated that a negligible decrease in the weight loss reduction was reported as NS dosages increased in the geopolymer concrete specimens. Mahboubi et al. (2019) reported that the weight loss of geopolymer concrete decreased in an acidic environment when nano-clay and nano-silica were added to the mixture proportions of geopolymer concrete. Similar findings for enhancing weight loss were made by Vyas et al. (2020) and Etemadi et al. (2020), who examined the durability performance of geopolymer concrete modified with various dosages of NS using solutions of 10% sodium chloride, 8%, and 10% sodium sulfate, and 5% sulfuric and hydrochloric acid.

The second phase of this study looked at the effect of varied RPA dosages as a natural fine aggregate replacement on the weight loss of GPC mixes in an acidic environment. As shown in Figure 6, replacing natural fine aggregate with RPAs negatively influences the weight loss of GPC mixtures; these effects became more pronounced as the replacement levels increased. The weight loss of GPC mixtures was 3.19%, 3.28%, 3.42%, 3.58%, 3.72%, and 3.95% at the natural sand replacement levels of 5, 10, 20, 30, 40, and 50% by RPAs, respectively, when the GPC samples were immersed in an acidic media for about 90 days. These results were greater than the control GPC mixture by 2.24%, 5.13%, 9.62%, 14.74%, 19.23%, and 26.6% for the previous RPA contents. Furthermore, when the time of immersion of the GPC samples in an acidic environment increased for around six months, the weight loss in GPC specimens increased compared to 90 days of exposure. For example, the average weight loss for the control GPC mixture without any dosages of RPAs was 4.21%; however, as sand replacement percentages increased, this value increased, reaching 5.74% for GPC having 50% RPA as fine aggregate replacement, which is 31.35% more than the weight loss in control GPC specimen. For the other RPA doses of 5, 10, 20, 30, and 40%, the weight decline was 4.37%, 4.52%, 4.74%, 5.04, and 5.29%, respectively. These findings were comparable to the weight losses of the GPC mixtures of 3.8%, 7.36%, 12.59%, 19.71%, and 25.65%, respectively, when compared to virgin GPC samples, in the GPC as mentioned earlier mixture orders. These outcomes were linked to the fact that the RPAs added to the GPC mixtures increased the concrete's porosity, allowing the acidic solution to more easily travel inside the concrete and, as a result, degrade GPCs in more places, as Akcaozog˘lu and Ulu (2014) stated that increasing PET aggregate amount caused the more porous structure of all mixtures. The porosity ratio of the control mixture increased from 18.1% to 30.9% when the PET aggregate amount was 100%. Since the second and third phases of this study's research regarding the resistance of GPC in an acidic environment are unique, it would be interesting to compare the current findings to those of earlier studies that used GP material without waste plastic aggregates. Bhutta et al. (2014) studied the durability of GPC exposed to a 5% sodium sulphate solution for over a year. Weight loss and compressive strength enhancement were observed. Compressive strength was superior to that of OPC concrete, and they concluded that GPC could be used to make sulphate-resistant concretes.

The optimum NS doses discovered in the first stage of this investigation have been added to the GPC mixtures with the prior RPA dosages as one of the strategies to address the negative effects of adding RPAs to the GPC mixtures. Compared to their reference GPC mixes without NS dosages, the weight loss values for those GPC mixtures containing 3% NS were lower. This is due to a higher level of partial pore filling with NS, which results in fewer "open" pores for the entry of acidic solution. Consequently, reduced weight loss was observed. The weight losses for the natural fine aggregate replacement levels of 5, 10, 20, 30, 40, and 50% were 2.62, 2.78, 3.10, 3.41, 3.61, and 3.85%, respectively, when the GPC mixtures were submerged in an acidic environment for roughly three months. These weight losses are less than the weight losses of the control GPC specimens by 16.03%, 10.9%, and 0.64% for RPA contents of 5%, 10%, and 20%, respectively; however, the weight losses for the remaining GPC mixtures are greater than the weight losses of the control GPC sample by 9.29%, 15.71%, and 23.4% for the remaining GPC mixes in the same preceding orders. Contrarily, it was discovered that the weight losses were reduced by 17.87%, 15.24%, 9.36%, 4.75%, 2.96%, and 2.53% for the RPA percentages of 5, 10, 20, 30, 40, and 50%, respectively, when compared to their reference mixes without any dosages of NS. It was clear that adding NS to GPC mixtures was crucial, as it significantly reduced weight loss in GPC mixtures G12, G13, and G14 compared to the control mixture.

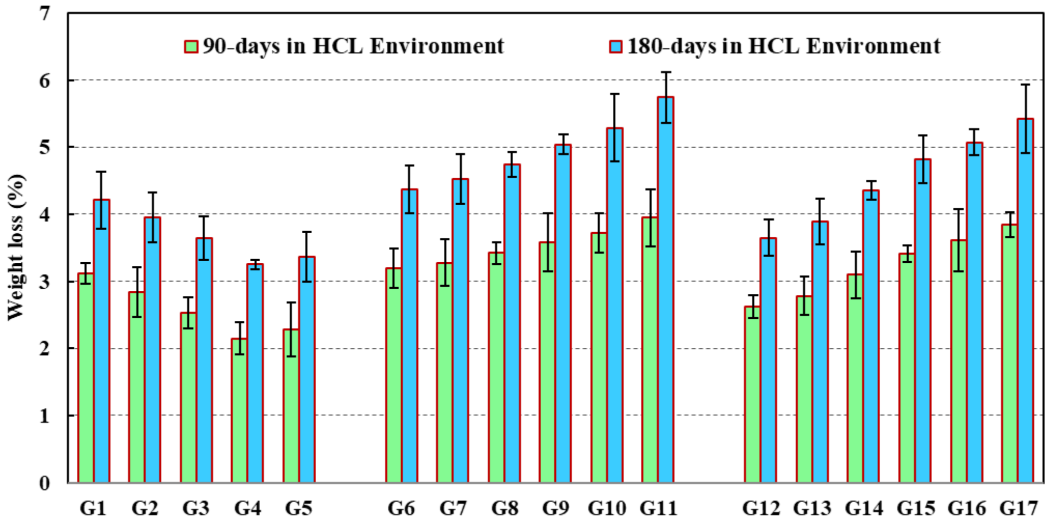


Fig.6: Weight loss of GPC mixtures with and without NS and RPA exposed to an acid environment

3.2.2.3. Residual compressive strength

To create durable concrete that can endure strong acid attacks, it is necessary to choose the right materials. Concrete constructions exposed to harsh environments of acidic ions can significantly limit their service life (Zhuang et al., 2016). Figure 7 displays the results of the compressive strength of GPC with and without different percentages of NS and RPA under standard water curing conditions and 5% hydrochloric acid (HCL) environments. The residual compressive strength values for all the GPC mixtures at 90 and 180 days of exposure to 5% HCL are higher than their compressive strength values that were cured under ambient conditions. Therefore, the residual compressive strength of all GPC mixes was compared to their compressive strength when cured under the same conditions as normal traditional concrete composites. Overall, as the age of the samples inside the HCL solution increased from 90 to 180 days, the compressive strength of the geopolymer concrete specimens decreased; however, the incorporation of NS improved the strength values, whereas the incorporation of RPAs decreased the strength of the GPC specimen.

The residual compressive strength was improved as the dosages of NS increased up to 3%, and then, it was slightly decreased. For instance, the compressive strength of geopolymer concrete mixtures at 1, 2, 3, and 4% of NS content dropped by 9.87%, 7.78%, 6.24%, and 7.29%, respectively, at the 90 days of HCL solution exposure, compared to their compressive strengths under water curing conditions; while the compressive strength of the control GPC mixture was reduced by 12.5% in comparison to its compressive strength in water curing regimes. In the same context, when the length of immersion in the acidic environment increased to 180 days, the residual compressive strength of all GPC mixtures decreased further. The residual compressive strengths of the GPC mixtures were 30.2, 38.4, 43.4, 48.6, and 44.9 MPa for the loading rates of NS of 0, 1, 2, 3, and 4%, respectively. These values were decreased by 27.2%, 19.3 %, 15.6 %, 10.8 %, and 13.8%, compared to their compressive strengths in water curing conditions, in the same preceding mixture sequences. These findings also showed that adding NS to the geopolymer mixture made the GPC specimens more resilient to acidic conditions. Generally, the destruction of the oxy-aluminum bridge (-Al-Si-O) of geopolymeric gel may be responsible for the loss of strength of geopolymer concrete specimens subjected to acid attack (Chindaprasirt et al., 2013). The reasons behind enhancing the residual compressive strength of the nano-geopolymer concrete specimens were argued to be those mentioned in the previous section (weight loss in HCL environment). Similar results for improving the compressive strength of geopolymer concrete have been observed in the literature; for example, tests by Çevik et al. (2018) demonstrated that the addition of 3% NS to geopolymer concrete reduced the weight loss from 7 to 15, and 32 to 5%, 11, and 19% when the geopolymer concrete specimens were exposed to seawater, magnesium sulfate, and sulfuric acid, respectively. In addition, it was observed that the loss of residual compressive strength in geopolymer mortar samples lacking NS ranged from 30 to 41%, whereas the loss of compressive strength in specimens including 2% of NS was between 9 and 11% when the geopolymer concrete specimens exposed to 3% of sulfuric acid solutions (Deb et al., 2016). Furthermore, tests by Patel et al. (2015) reported a negligible decrease in the residual compressive strength as NS dosages increased in the geopolymer concrete specimens. According to Mahboubi et al. (2019), when nano-silica was added to the geopolymer concrete mixture proportions, the residual compressive strength of the samples was improved in an acidic environment.

Figure 7 shows that adding RPAs to GPC mixtures as a natural sand replacement causes a reduction in residual compressive strength; these unfavourable impacts grew with the addition of more RPAs. The residual compressive strength of the GPC specimens was found to be 40.2, 38.8, 35.9, 33.7, 29.5, and 23.2 MPa for the natural fine aggregate replacement levels of 5, 10, 20, 30, 40, and 50% by RPAs, respectively, after being submerged in 5% HCL solution for around three months. These results were equivalent to the decrease in compressive strength of 14.68%, 17.27%, 22.56%, 28.49%, 35.93%, and 41.38% in the same previous GPC mixture orders, as compared to their samples in the standard water curing conditions. Furthermore, after six months of GPC exposure to the HCL environment, the residual compressive strength was lowered much more than after three months of HCL exposure circumstances. The decrease in the compressive strengths of GPC specimens was 29.35%, 32.22%, 36.49%, 38.87%, 43.39%, and 47.84% under 5% HCL environment, for the replacement level of natural fine aggregate of 5, 10, 20, 30, 40, and 50% by RPAS, respectively, in relative to their compressive strength in the normal water curing regimes. However, this decline in the compressive strength was slightly lower for the control GPC samples without any dosages of RPAs. The poor bond between the GPC matrix and the RPAs' surfaces and more pores and voids within the GPC structures were cited as the causes of these test results. These pores and voids make it easier for acidic substances to enter the GPC specimens, which adversely affects the bond between the RPA particles and the GPC matrix and lowers the strength of the GPC specimens. The porosity of specimens, pore size, connectivity of pores, and the presence of Na-rich gel in the geopolymer gel structure have all been found to be strongly correlated with the acid resistance of geopolymers (Djobo et al., 2016). In addition, the depolymerization of the aluminosilicate polymers in an acidic media and the formation of zeolites were reported for the reduction in the strengths of geopolymer composites (Bakharev, 2005).

In the last part of this study, NS with 3% by weight of the total binder content was added to the GPC mixtures that included various doses of RPAs to strengthen the bond between the surface texture of the RPAs and the GPC matrix system. It was observed that, despite the specimens being exposed to sulfuric acid environments for about three and six months, the addition of the optimal dosages of NS to the GPC mixtures with different percentages of RPAs significantly increased the residual compressive strengths of the GPC samples. The NS addition to GGBFS-based GPC specimens incorporated various volumes of RPAS increased the residual concrete strength due to the lower porosity and the denser structure. The lowest compressive strength reduction was observed in the GPC mixture with 5% RPA content, while the maximum reduction was observed for the GPC mixture with 50% RPA dosages. For instance, the compressive strengths of the GPC samples dropped under 5% of HCL solution environments by 8.94%, 11.60%, 17.01%, 23.54%, 29.24%, and 37.31%, respectively, compared to their strengths under the typical water curing circumstances for the dosages of RPAs of 5, 10, 20, 30, 40, and 50%, respectively.

At the age of 180 days of exposure, the average residual compressive strength value for the virgin GPC samples was 30.2 MPa (compared to its strength value of 36.3 MPa at 90 days of acidic exposure); however, when 3% of NS was added to the GPC mixtures with varying contents of RPAs, this value increased up to 20% of RPAs, and subsequently decreased. For instance, adding 3% of NS in GPC mixtures with natural sand replacement levels of 5%, 10%, and 20% by RPA improved the residual compressive strength to 40.8, 36.8, and 31.2 MPa, correspondingly. However, these compressive strength values were decreased by 17.07%, 22.36%, and 28.28% compared to the compressive strengths of respective reference mixes cured in the standard water condition. Moreover, the residual compressive strength values further decreased to 26.8, 21.4, and 14.4 MPa, for the 30, 40, and 50% of RPA contents, respectively. On the other hand, these results were felt by 32.15%, 37.43%, and 46.27% compared to their comparable mixes in the same previous order of RPA dosages when cured in water conditions. The reasons for these findings were the same as those covered in the previous paragraphs.

Finally, Figure 8 shows the compressive strength failure modes of G1 (control), G4 (3%NS), G8 (20%RPA), G10 (40%RPA), G14 (20%RPA+3%NS), and G16 (40%RPA+3%NS) with and without various NS and RPA dosages after exposing to acidic environments of about 90 days. After testing, the control concrete specimens and those exposed to different NS dosages were substantially split in half and had numerous tiny cracks, indicating a brittle failure mechanism. The situation was slightly different for the other samples since they contained scattered RPAs, as it was shown that adding RPAs to GPC mixtures made the specimens behave more ductility than those GPC mixtures that did not. With an increase in sand replacement level, this tendency becomes more prominent.

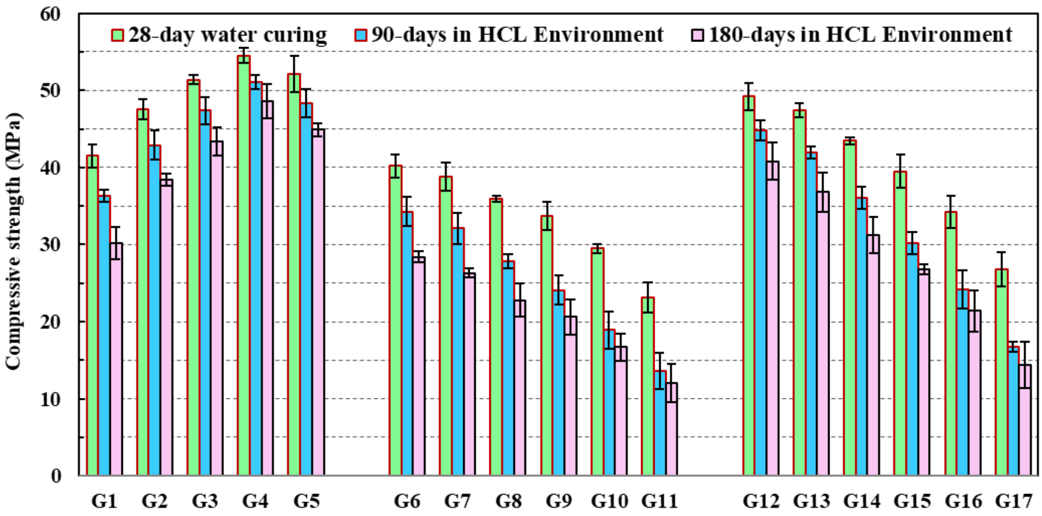


Fig.7: Compressive strength of GPC mixtures with and without NS and RPA exposed to an acid environment

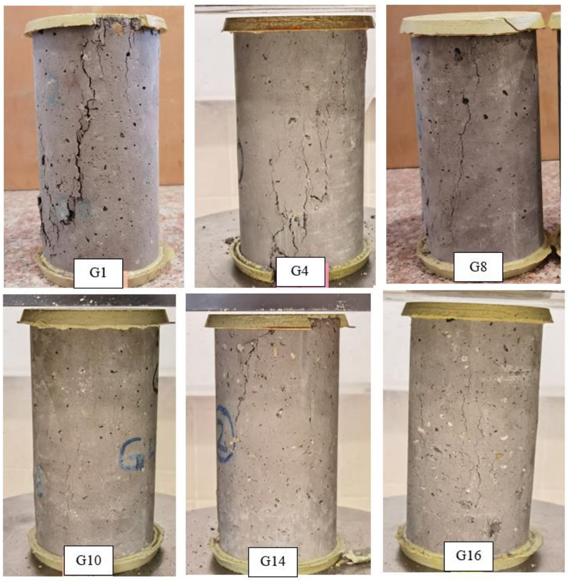


Fig.8: GPC specimen failure patterns under compression test after exposure to an acidic environment

3.2.3.Rapid chloride permeability test (RCPT)

The findings of the RCPT value in coulombs of GPC incorporated different percentages of NS and RPAs after 90 days are displayed in Figure 9. Overall, the RCPT value fell for all GPC mixtures with varying NS loading rates, with the highest value obtained for a mixture containing 4% of NS; nevertheless, the RCPT value improved slightly when the NS dosages were altered from 3% to 4%. While, the inclusion of various contents of RPA leads to an increase in the value of RCPT results. Concrete's resistance to chloride penetration is one of the most important factors impacting its resilience to corrosive environments (Kohail and Khalaf, 2021). Classification of chloride penetration levels is based on the charge passed through specimens, as prescribed by ASTM C1202 standard. Based on the charge that traveled through the GPC specimens, it is clear that most of the GPC mixture responses fell into the moderate class categories since the value of the RCPT was in the range of 1965-4065 coulomb.

The outputs of the RCPT values for the NS dosages of 0, 1, 2, 3, and 4% are 3045, 2540, 2275, 1980, and 1965 coulombs, respectively, after the GPC specimens had been in the test condition for around 6 hours. It is obvious that adding NS significantly increased the GPC mixes' resistance to chloride ions infiltration. The classes of the GPC specimens were changed from those with moderate levels to those with low chloride permeability upon adding 2, 3, and 4% of NS to the GPC mixtures. For the same previous GPC orders, these improvements were 16.58%, 25.29%, 34.98%, and 35.47% concerning the GPC control mixture. This improved RCPT value was attributable to the fact that NS with a well-distributed and homogenous dispersion could significantly improve particle packing in geopolymer concrete, resulting in a more compacted and denser microstructure, and as a consequence, chloride penetration was decreased and improved (Ahmed et al., 2022a); moreover, lower RCPT value means that there are more crystalline compounds in nano-silica modified geopolymer concrete, the diffusion coefficient will be lower. This will make the material last longer and be more durable (Adak et al., 2014). Similar results have been reported in the literature even though different NPs were used in geopolymer concrete composites. For example, according to Adak et al. (2014, 2015), adding colloidal nano-silica, hybrid NS, and nano-silver to the geopolymer mortar mixtures improved the RCPT value compared to control geopolymer mortar mixtures. Also, Sastry et al. (2021) looked at how the strength and durability of fly ash-based geopolymer concrete composites changed when NT was added in different amounts (0, 1, 2, 3, 4, and 5%). They revealed that the amount of charge (in coulombs) that went through the geopolymer concrete specimens was less than the control mix up to 3% of NT dosages, and then it went up.

The RCPT was also employed in the second part of this investigation to demonstrate the endurance properties of GPC mixtures, including varying percentages of RPAs. As previously stated, adding RPAs to GPC mixtures causes an increase in chloride permeability levels. It was demonstrated that increasing the RPAs in the GPC mixtures raised the RCPT values. The RCPT values were 3180, 3280, 3450, 3580, 3750, and 4065 coloumbs, for the loading rates of RPAs of 5, 10, 20, 30, 40, and 50%. Except for the 50% RPA doses, which were in the high class of chloride permeability level, these values fell into the moderate chloride permeability category. For the prior mixing sequences, these findings were, respectively, 4.43%, 7.72%, 13.3%, 17.57%, 23.15%, and 33.50% higher than the control GPC mixture. These results were attributed to the fact that adding RPAs creates more pores and voids within the GPC mixtures; as sequence, RCPT values were increased. Even though different RPA doses were utilized for sand and gravel replacement, similar outcomes have been reported in the literature for traditional concrete composites (Silva et al., 2013).

Nano-silica with optimal doses has been used as one of the strategies in the third phase of this investigation to address the detrimental effects of adding RPAs on the properties of the GPC mixtures. Overall, it was found that incorporating NS improved the RCPT values; this improvement was dropped as the dosages of RPAs increased within the GPC mixtures. For instance, the inclusion of 3% of the NS decreased the RCPT values from 3180, 3280, 3450, 3580, 3750, and 4065 coloumbs into 2405, 2585, 2865, 3260, 3540, and 3890 coloumbs, for the natural fine aggregate replacement levels of 5, 10, 20, 30, 40, and 50% by RPAs, respectively. These changes in the RCPT outputs were comparable to the enhancement in the RCPT values by 24.37%, 21.19%, 16.96%, 8.94%, 5.6%, and 4.3%, respectively, for the GPC mentioned above mixtures sequences. In addition, even though RPAs replaced 50% of natural sand, the addition of NS caused the GPC mixture's class to change from high chloride permeability levels to moderate levels. Furthermore, on the other hand, the RCPT values were lower than the control geopolymer concrete samples by 21.02%, 15.11%, and 5.91% for the RPA percentages of 5, 10, and 20%, correspondingly; while further increment in the contents of RPAs leads to rose the RCPT value by 7.06%, 16.26%, and 27.75% for the 30, 40, and 50% of RPAs, respectively, even though 3% of NS was used for improving its properties. These findings supported the claim that adding NS to the GPC mixes improved the microstructure of the composite by producing more geopolymerization products and filling pores and voids in the GPC matrix.

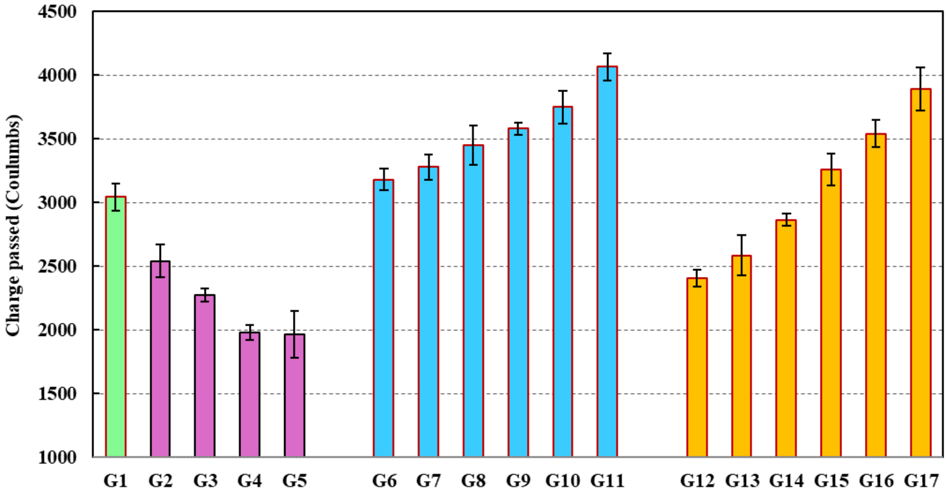


Fig.9: RCPT values of GPC mixtures with and without NS and RPA at the age of 90 days

1. Conclusions

Extensive laboratory experiments were carried out on recycled plastic aggregate geopolymer concrete that was modified with nano-silica, and based on the results obtained, certain conclusions were drawn:

1. As the percentage of NS in the geopolymer concrete mixtures was increased, the compressive strength also increased up to 3%, but then it started to decrease. However, the compressive strength of the GPC mixtures significantly decreased when RPAs were added.
2. Adding 3% NS to those geopolymer concrete mixtures containing varied dosages of RPAs improves compressive strength and minimizes the disadvantage of RPA addition. In 28 days, compressive strength improved by 20.4, 20.3, 16.9, 14.8, 14.2, and 10.9% at 5, 10, 20, 30, 40, and 50% RPA contents, respectively, compared to their compressive strength without any NS doses.

3. Geopolymer concrete has been found to exhibit better performance in standard water curing conditions compared to ambient curing conditions. Similarly, adding NS had a more significant impact on the performance of geopolymer concrete when cured in water than when cured in ambient conditions.
4. The water absorption of all geopolymer concrete mixtures with varying dosages of NS was significantly improved. The maximum improvement was nearly similar for 2 and 3% of NS content, which was 32.2 and 38% at 28 and 90 days, respectively, compared to the control geopolymer concrete mixture. However, water absorption increased dramatically with increasing RPA dosages.
5. Geopolymer concrete mixtures containing 5, 10, 20, 30, 40, and 50% RPA and modified with 3% NS exhibited reduced water absorption by 20.6%, 18.8%, 9.7%, 7.6%, 6.2%, and 5.4%, respectively, compared to GPC mixtures without NS.
6. Geopolymer concrete mixtures with the inclusion of NS exhibited greater resistance to acidic conditions than control specimens, as demonstrated by colour and appearance changes, weight loss, and residual compressive strength. However, with the increment in RPA dosages, the resistance of GPC specimens to the acidic environment was decreased.
7. The addition of NS improved residual compressive strength in GPC mixes containing different RPA dosages. After exposure to an acidic environment for 90 days, NS enhanced residual compressive strength by 30.6, 30.5, 29.8, 25.3, 28, and 23.5% for GPC mixes with 5, 10, 20, 30, 40, and 50% RPA, respectively, compared to similar samples without NS.
8. Increasing NS dosages significantly reduced RCPT values in GPC samples, with the greatest improvement observed at 3% and 4% dosages resulting in a 35% reduction in RCPT values after 90 days compared to controls. Additionally, NS improved electrical resistivity and bulk electrical conductivity, with maximum enhancements at 3% and 4% dosages resulting in around 36.7% and 32% increases after 90 days compared to controls. However, adding RPAs in to the GPC mixtures negatively impacted on these test results.

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