DURABILITY OF GEOPOLYMER CONCRETE WITH RECYCLED SAND IN ACIDIC AND MARINE CONDITIONS

[a] Shahzadi Irum*, [b] Faisal Shabbir, [c] Hammad Salahuddin

a: Civil Engineering Department, COMSATS University Islamabad, Wah Campus, Pakistan. Irum.jawad@ciitwah.edu.pk
b: Department of Civil Engineering University of Engineering & Technology Taxila, Pakistan. faisal.shabbir@uettaxila.edu.pk
b: Department of Civil and Transportation Engineering, Shenzhen University, China. Hammads88@szu.edu.cn
* Corresponding author

Abstract- Incorporating recycled sand (R-sand) in geopolymer concrete (GC) not only enhances environmental sustainability by utilizing industrial by-products and construction & demolition waste but also reduces dependency on river sand, making it a more environmentally friendly option. This paper presents an experimental investigation on the behavior of GC with R-sand in acid and marine water. All samples were prepared with a combination of fly ash and slag as a binder, using sodium hydroxide and sodium silicate as alkaline activators. The specimens were exposed to 4% sulfuric acid and artificial marine water for a period of 60days. The parameters that were examined during the experimental investigation are compressive strength, compressive strength loss, mass loss, and water absorption. The results show that the strength of GC gradually reduced with an increased R-sand content, and it performs better in marine water as compared to acidic solution.

Keywords- Acid and Marine Water, Durability of Concrete, Geopolymer Concrete, Recycled Sand

1 Introduction

Geopolymer concrete (GC) is gaining considerable attention as a sustainable alternative to traditional Ordinary Portland Cement (OPC) concrete. Despite its widespread use, OPC concrete has notable environmental drawbacks, including high energy consumption and significant carbon dioxide emissions, contributing to climate change [1]. Moreover, OPC concrete is susceptible to degradation when exposed to aggressive environments such as acidic and chloride-rich conditions change [2]. In contrast, GC offers several advantages, including a lower carbon footprint and enhanced resistance to chemical attacks. GC is synthesized by activating aluminosilicate-rich industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin with alkaline solutions, typically a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) [3].These binders contribute to improved mechanical performance [4] and superior durability properties under aggressive exposures [5].

Aggregates, both coarse and fine, constitute approximately 75% to 80% of the total volume of GC [6]. With the increasing scarcity of natural sand and environmental concerns over riverbed mining, the replacement of natural aggregates with recycled alternatives, particularly recycled sand (R-sand) derived from construction and demolition (C&D) waste has become a key area of interest [7], [8]. The use of R-sand not only helps conserve natural resources but also facilitates waste management by diverting C&D waste from landfills. However, the application of R-sand in GC remains limited, especially in comparison to recycled coarse aggregates [9], [10].

Due to its dense and homogeneous matrix, GC has demonstrated promising durability under aggressive environments, such as acid and marine exposure[11], [12]. Structures located in urban and coastal areas frequently deteriorate after prolonged exposure to acidic media, sulfates, or chlorides [13]. GC, with its low calcium content and stable aluminosilicate structure, has shown greater resistance to such deterioration than OPC-based systems.

Despite these advantages, there is limited research focusing specifically on the durability of GC incorporating R-sand under aggressive conditions such as acid and seawater. This study aims to bridge that gap by evaluating the performance of GC mixes with varying proportions of R-sand under acid and marine water. Understanding the influence of R-sand on the durability of GC will provide valuable insights for the practical implementation of sustainable and durable construction materials. Furthermore, promoting the use of recycled aggregates in GC contributes to the circular economy and the reduction of the construction industry's carbon footprint.

2 Research Methodology

2.1 *Material properties*

In this study, a composite binder was developed using 80% locally sourced Class F fly ash and 20% GGBFS. The chemical composition of the Class F fly ash included SiO_2 (48.6%), Al_2O_3 (32.23%), CaO (3.24%), MgO (2.02%), Na_2O (4.45%), TiO_2 (2.02%), and Loss on Ignition (LOI) at 1.63%. The GGBFS contained SiO_2 (30.12%), Al_2O_3 (14.7%), Fe_2O_3 (10.3%), CaO (34.25%), MgO (5.1%), Na_2O (0.28%), TiO_2 (0.36%), and LOI (2.69%).

The alkaline activator system consisted of a sodium silicate (Na_2SiO_3) solution—composed of 29.4% SiO_2, 14.6% Na_2O, and 56.0% H_2O—and a 12M sodium hydroxide (NaOH) solution. Natural river sand was used as natural fine aggregate, while natural coarse aggregates (NCA) were obtained from a nearby quarry. R-sand were prepared from previously tested concrete specimens produced under controlled laboratory conditions (28-30MPa). The water absorption rates for R-sand and natural sand were found to be 5.6% and 0.92%, respectively.

2.2 *Specimen Preparation*

12M NaOH solution was prepared by mixing 97–98% pure pellets with water, 24h before the concrete mixing. The alkaline activator was made by mixing Na_2SiO_3 and NaOH solution 1h before casting. Aggregates were dry mixed with binder for 2 minutes, followed by gradual addition of the alkaline activator solution. Mixing persisted for an additional 2-3 minutes before pouring the mixture into molds and compacting it using a vibration table. Specimens were removed from molds after 24 hours and were hot cured at 80 °C for the next 24 hours, followed by storage at ambient temperature until the age of testing. Figure 1 shows the raw materials, mixing, casting and samples under acid and seawater.

2.3 *Mix Design*

The mix proportions of the GC utilized in this study are detailed in Table 1. A total of four GC mixtures were prepared, incorporating varying proportions of R-sand to evaluate its influence on the performance of the concrete. The S0 (control specimen) was made with NCA and N-sand. R-sand with 30%, 60%, and 100% replacement of N-sand was used.

Table 1 Mix design of GC with R-sand

Mix ID	**Binder**		**Alkaline Activator**		**Coarse and Fine Aggregates**		
	FA	**GGBFS**	**Na_2SiO_3**	**NaOH**	**NCA**	**N-sand**	**R-sand**
S0	320	80	171.4	68.6	1144	616	0
S30	320	80	171.4	68.6	1144	431	185
S60	320	80	171.4	68.6	1144	185	431
S100	320	80	171.4	68.6	1144	0	616

2.4 *Testing*

Compressive strength testing was conducted in accordance with ASTM C39 [14], at 7 and 28 days. To estimate the durability of the concrete more rapidly, water absorption was assessed following the [15] standard. Resistance to marine water was evaluated using the ASTM D1141[16] procedure, where synthetic seawater was prepared and cylindrical specimens (100 mm × 200 mm) were submerged for a period of 60 days. Subsequently, compressive strength and weight measurements were recorded to calculate the percentage reduction in strength and mass. Additionally, to assess the acid resistance of the GC samples, ASTM C267[17] was followed. Specimens were immersed in a 4% sulfuric acid solution after initial weighing, and after 60 days of exposure, changes in physical appearance, compressive strength, and weight were documented to determine deterioration.

a) b)

c) d)

Figure 1: a. Materials b. Mixing c. Seawater test d. Acid test

3 Results

3.1 Compressive Strength

Figure 2 illustrates the compressive strength results of all the mixes. The control mix (S0) exhibited the highest 28-day compressive strength, reaching 41.2 MPa. When river sand was partially replaced with R-sand, a gradual reduction in compressive strength was observed—recorded as 4.37%, 12.86% and 31.55% for S30, S60, and S100, respectively. At replacement levels up to 60%, the reduction was comparatively moderate (12.86%) relative to the significant decline (31.55%) seen at 100% substitution. This trend can be partly attributed to the finer particles present in the recycled sand, which may have contributed to enhanced packing density and reduced voids in the matrix [8]. However, as the proportion of recycled sand increased, the presence of old adhered mortar from parent concrete became more pronounced, adversely affecting the mechanical bonding and ultimately reducing the compressive strength of the geopolymer concrete [18].

The strength development of GC was notably enhanced by heat curing, with all mixes attaining approximately 80–90% of their 28-day strength within the first 7 days, as illustrated in Figure 2. After this initial period, strength gains progressed at a slower rate until day 28. The inclusion of R-sand slightly reduced the early strength gain rate. The S0, incorporating only natural sand, achieved 91.02% of its 28-day strength by the 7th day. In comparison, mixes S30, S60, and S100 reached 87.82%, 89.14% and 85.46% respectively, of their 28-day strength within the same duration. Comparable observations were reported by Zhang et al. [18], who studied ultra-high-performance concrete (UHPC) with R-sand. This reduction in early-age strength gain was primarily attributed to an increased effective water-to-binder ratio in mixes containing R-sand [10], [19].

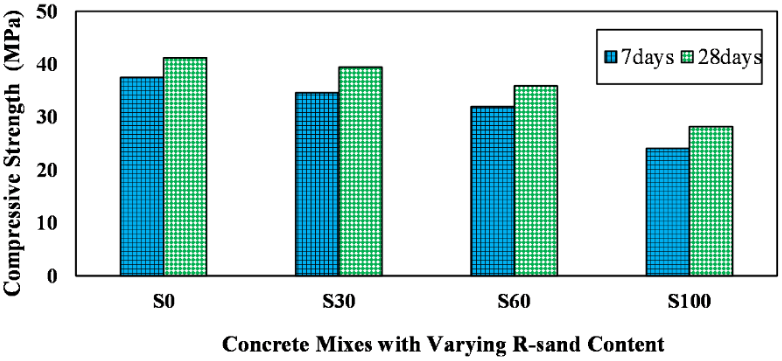

Figure 2: Compressive Strength (MPa) of different mixes at 7 and 28 days

3.2 Compressive strength Loss

Figure 3 presents the percentage loss in compressive strength for specimens subjected to 60-day exposure in 4% sulfuric acid and synthetic marine water. For the S0, strength losses were 3.88% under acidic conditions and 1.46% in the marine water. With the incorporation of R-sands, the loss in compressive strength increased to 4.31%, 6.41% and 12.06% in the acidic medium, and to 3.05%, 5.57% and 7.09% under marine conditions for mixes S30, S60, and S100, respectively. GC demonstrated excellent durability in aggressive environments due to its low calcium content and reduced water absorption capacity [20], [21]. GC tends to develop a dense and chemically stable aluminosilicate matrix, which limits pore connectivity and hinders aggressive ion penetration [22]. Mixes with lower R-sand content likely maintained lower porosity and better matrix integrity, contributing to reduced strength and mass loss. Conversely, higher replacement levels may introduce voids or weak interfaces, increasing vulnerability to chemical degradation.[11], [23]. The inferior performance in acidic conditions can be linked to the residual cement paste attached to R-sand, which tends to degrade upon acid exposure, resulting in microcracking and subsequent reductions in both mass and strength [24], [25]. Furthermore, R-sand exhibits higher vulnerability to acid attack compared to N-sand [19]. This heightened susceptibility of finer recycled aggregates is often attributed to their larger specific surface area, which increases their interaction with aggressive agents, leading to more pronounced chemical deterioration [8], [19].

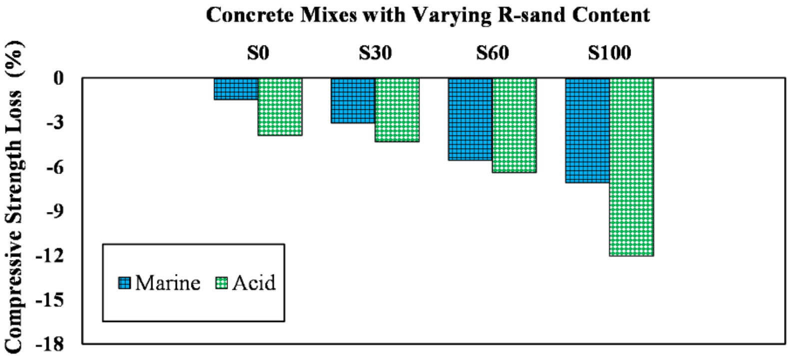

Figure 3: Compressive Strength loss (%) of GC incorporating R-sand after 60 days of exposure to acidic and marine conditions

3.3 Mass Loss in acidic and marine conditions

Figure 4 illustrates the mass loss of GC specimens exposed to acidic and marine environments. Specimens containing natural aggregates demonstrated strong resistance, exhibiting no noticeable surface degradation, cracking, or fracturing under either exposure condition. However, the inclusion of R-sand led to evident surface erosion and an increase in mass loss. The control mix experienced a minimal mass loss of 0.76% in the acidic environment and none in the marine environment. This superior durability is primarily attributed to the rapid polymerization reaction facilitated by elevated temperature curing in GC, which is more efficient than that in OPC systems [13]. The recorded mass loss for S30, S60, and S100 in the acidic medium was 1.61%, 3.05% and 4.21%, respectively. Corresponding losses in the marine condition were 3.04%, 5.13%, and 6.71%. Mass loss was considered as the combined outcome of surface erosion and chemical degradation caused by exposure to aggressive environments. Similar findings were reported by Mahmood et al. [26], who observed that the use of recycled aggregates in concrete compromised its performance by reducing compressive strength, increasing porosity and chloride permeability, and weakening the bond strength in marine exposures. The dense microstructure developed through geopolymerization significantly minimizes the permeability of the matrix, thereby improving resistance to aggressive environments such as acids and seawater [23], [27], [28].

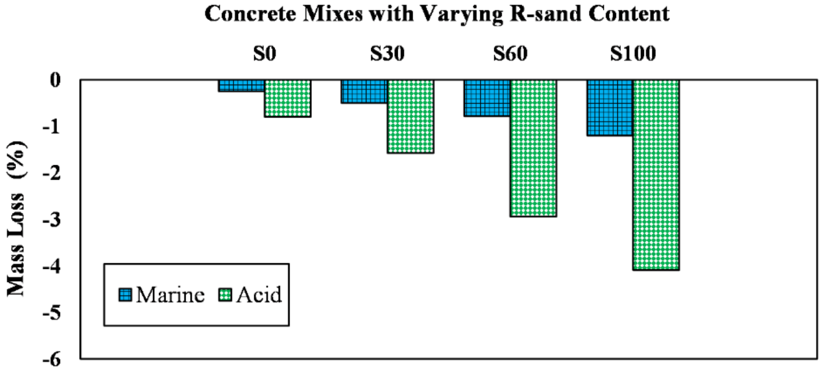

Figure 4: Mass loss (%) of GC incorporating R-sand after 60 days of exposure to acidic and marine conditions

3.4 Water absorption

Figure 5 presents the water absorption results of the cylindrical specimens tested at 28 days. The control mix exhibited a water absorption of 5.6%, while the values recorded for S30, S60, and S100 were 6.18%, 6.45%, and 8.58%, respectively. A consistent increase in water absorption was observed with the progressive replacement of natural sand (N-sand) by R-sand, from 0% up to 100%. This rise in absorption is primarily attributed to the porous nature of R-sand, particularly due to the adhered mortar, which tend to retain more moisture [10], [18], [19], [29]. Moreover, the inherently higher water absorption capacity of R-sand compared to N-sand further contributed to this trend. Notably, the S100 mix demonstrated a 36% increase in water absorption relative to the control mix.

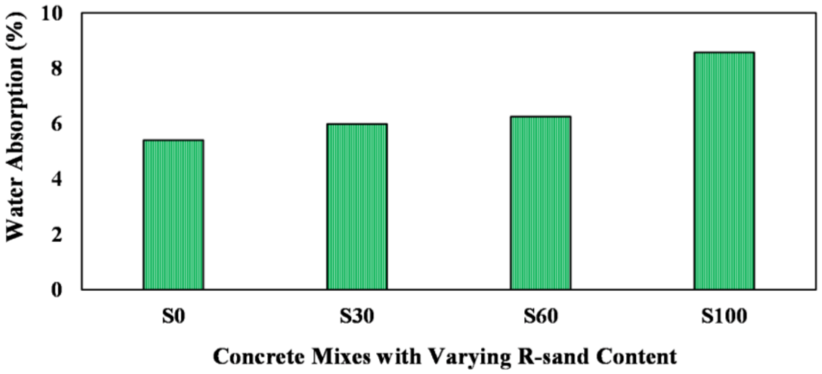

Figure 5: Water Absorption (%) of GC incorporating various percentages of R-sand

4 Practical Implementation

The utilization of R-sand in GC presents a promising solution to address sustainability challenges and reduce reliance on natural resources such as river sand. This approach enhances sustainability by incorporating recycled materials and reducing environmental impact. In practical applications, this research demonstrates that R-sand can be effectively used in GC exposed to acidic and seawater environments, offering a viable and sustainable alternative to natural sand. The findings support the use of R-sand-based GC in coastal and industrial structures, where chemical exposure is prevalent.

5 Conclusion

Based on the findings of this study, the following conclusions can be drawn:

1. Natural sand can be entirely substituted with R-sand, as the 28-day compressive strength of the fully replaced mix (S100) remained above 28 MPa.
2. Compressive strength decreased with higher R-sand replacement, showing a moderate reduction (12.8%) at 60% replacement and a substantial loss (31.5%) at full replacement.
3. In acidic environments, specimens with 100% R-sand exhibited the highest compressive strength loss at 12%, while mixes containing only N-sand showed less than 4% loss. The increased vulnerability of R-sand to acid attack becomes more pronounced with higher replacement ratios.
4. GC specimens prepared with N-sand demonstrated excellent resistance to marine conditions. Even with full replacement by R-sand, the loss in compressive strength remained minor (1.2%), and no significant mass loss was observed.

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