

Durability Assessment of Recycled Aggregate Geopolymer Concrete Mixed with Wastewater

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Abstract: The advancement of an environmentally friendly setting is complex due to the significant carbon footprint of cement, substantial construction and demolition waste, and large quantities of industrial waste wastewater. This study aims to increase building sustainability by analyzing the long-term durability of recycled aggregate geopolymer concrete (RGC) manufactured using four different wastewaters. To evaluate each wastewater's effect on sulfuric acid resistance and chloride ion migration (CIM) at various curing times, RGC was used in place of fresh water in the tests. The results revealed that, when it came to acid attack, RGC made with fertilizer industry wastewater had the highest mass loss (41% higher compared to control concrete) and CIM (29% higher compared to control concrete). According to statistical studies, using wastewater from textile, fertilizer, and sugar firms did not substantially alter mass loss from acid attack or CIM.

Keywords: Recycled aggregate concrete; acid attack; sustainability; chloride ion migration; chemical oxygen demand.

1. Introduction

Urbanization, population increase, and market circumstances in industrialized nations influence the amount of recycled aggregate concrete (RAC) produced by construction degradation. It is necessary to properly dispose of this construction and demolition waste to preserve a sustainable ecology. The RAC removes construction and demolition waste, consolidates transportation routes, and reduces carbon impact [1, 2]. Even though natural aggregate concrete has many advantages over RAC, including high water absorption (WA), low split-tensile strength, and high porosity, it dramatically improves ductility, which is one of the most appealing features [3]. The Portland cement manufacturing process produces CO₂ as a by-product. Researchers employed green concrete, often referred to as 'geopolymer concrete' (GPC), which is made from recycled coarse aggregates (RCA), to lessen the concrete constructions' carbon footprint. Silica fumes, blast furnace slag, fly ash, and red

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mud are alkaline activators used to create an inorganic alumino-silicate polymer binder in GPC concrete.

Moreover, a large amount of industrial waste and urban runoff are dumped into landfills and rivers. Once more, the need for other, more affordable disposal methods is growing as a result of severe environmental laws and the prohibition of open landfills close to populations. The second most commonly utilized material is concrete. There is a lack of fresh water. Rapid population expansion and increased economic activity have enhanced the availability of freshwater. One trillion gallons of water are consumed annually by concrete, the second most commonly used material in the world after wood [4]. Thus, freshwater consumption must be reduced to balance supply and demand, especially in the global building sector. [5]. As shown in the study, by 2020, half of the world's population would be thirsty [6]. Reusing waste, particularly in concrete, is becoming increasingly popular. The enormous cost of purifying sewage might be avoided by using it instead to produce concrete [7]. Contaminated water also has detrimental effects on human health and the natural ecosystem. Consequently, using waste from the production of concrete could help to partially offset these detrimental effects on the environment and living things.

Numerous studies have demonstrated using different kinds of wastewater in producing concrete and other building materials [8-11]. The use of recycled wash water in alkali-activated concrete was explored in detail, and it was discovered that recycled wash water had no detrimental impact on alkali-activated concrete growth [12]. Furthermore, mortar cubes manufactured from recycled treatment plant water had the same strength as freshwater mortar cubes [13]. The compressive performance of concrete made from treated wastewater was investigated in detail, and it was noticed that increasing the quantity of treated wastewater in the concrete improved the compressive strength (CS) by up to 28 days [14]. Furthermore, CS was increased by up to 1.5% when processed wastewater was used for curing. When treated domestic sewage is used rather than freshwater, the strength of the concrete is enhanced by 9%, while the setting time is unaffected [15]. Compared to freshwater concrete, wash-water concrete has a CS of 96% [16]. Using treated wastewater instead of freshwater improved the concrete's setting time and strength [17, 18]. During 180 days of testing with wastewater following the treatment, it was observed that the mix's CS had increased by 17%. The axial strength of secondary treated wastewater, on the other hand, has decreased by 18%. Furthermore, WA values were higher in concrete constructed with secondary treated wastewater [19].

The literature review indicates that wastewater and RCA in geopolymer concrete has not been investigated in the previous studies and can help develop more ecologically friendly products. A detailed analysis of the long-term properties of RGC derived from various waste kinds is required. This work aims to investigate the durability properties of RGC blends at different curing stages, such as resistance to sulfuric acid attack and chloride penetration, using a variety of wastewater types, including textile, fertilizer, and sugar factory wastewater named TE, FE, and SE respectively. For comparison, a freshwater-based RGC mix was created.

2. Materials and Methods

2.1. Materials

RCA was used to substitute coarse aggregates in the manufacture of RGC. The RCA was obtained by crushing concrete cylinders with a CS ranging from 30 to 45 MPa at 6 to 10 years of age. Table 1 displays the various qualities of recycled aggregates. The recycled aggregate has a maximum size of 10 mm. The Lawrancepur sand, which is readily accessible and has a fineness modulus of 2.25 and an apparent particle density of 2586 kg/m³, was used. The sieve analysis of the material utilized in this investigation is displayed in Figure 1. To ensure that the GPC mix is workable, a superplasticizer called Sika ViscoCrete®-3425 has been used. Class F fly ash (60%) and GGBS (40%) were used as binders in the RGC that were locally accessible. Table 2 lists many characteristics of fly ash. As an activator, a mixture of NaOH (14M molarity) and Na₂SiO₃ was used in a mass ratio of 1:2.5 A workability test was conducted on fresh RGC in accordance with ASTM C143/C143M-15 [20] and the results showed a slump value i.e. 100 mm. A setting time of 90 minutes was reported, according to ASTM C807-13 [21].

Table 1. Parameters of recycled aggregates

Quantity	Value	Quantity	Value
WA at 24 hours	6.62%	Apparent density	1723 kg/m ³
10% fine value	142KN	Minimum size	4.75 mm
Los Angeles abrasion	38.22%	Maximum size	10 mm
Bulk density	1316 kg/m ³	Specific gravity	2.23

Table 2. Composition of Fly Ash

Chemical property		Physical property	
Quantity	Value (%)	Quantity	Value
SiO ₂	55.4	Consistency [22]	29.2%
Fe ₂ O ₃	3.3	Fineness (Blaine Test)	2767 (cm ² /g)
Na ₂ O	1.8	Soundness [23]	No expansion
CaO	3.9	Specific surface area [24]	387 m ² /kg
Al ₂ O ₃	29.5	-	-
SO ₃	2.3	-	-

For RGC manufacture, four various kinds of waste were gathered from their origins. Freshwater was used to replace each type of wastewater completely. Table 3 summarizes the chemical characteristics of all wastewater types used in this study.

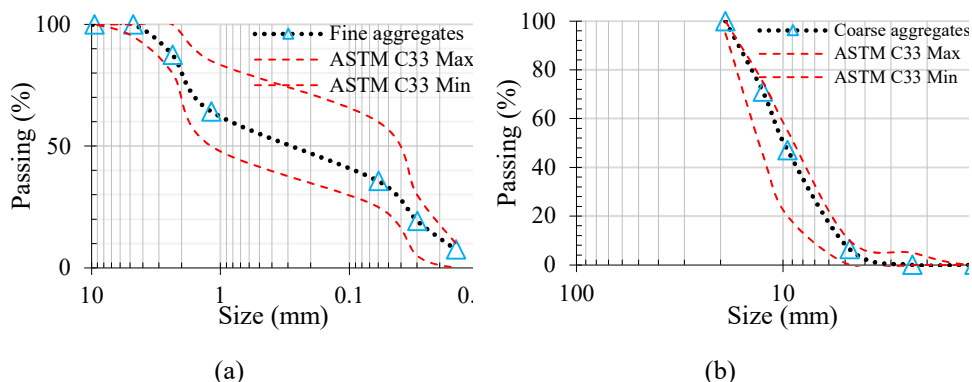


Figure 1. Granulometry (a) sand (b) RCA

Table 3. Chemical composition of wastewater(test results from PCRWR)

Parameter (unit)	FW	SE	FE	TE
pH value	7.0	7.2	2.5	7.0
COD (mg/L)	23	412	867	105
TSS (mg/L)	25	459	50.4	21
TDS (mg/L)	806	986	2547	344
BOD (mg/L)	12	268	528	64
DO (mg/L)	6	3	4	5
Hardness (mg/L)	325	648	2304	307
Fluoride (mg/L)	0.4	1.1	0.1	0.7
Iron (mg/L)	0.8	0.8	3.3	0.9
Chloride (mg/L)	11	306	945	57.1
Sulphate (mg/L)	6.6	679	405	94.5
Nitrate (mg/L)	1.3	92	59	2.6

2.2. Manufacture and Testing

The four RGC mixtures developed by combining various types of sewage were Fresh water(FW),sugar factory wastewater(SF), fertilizer factory wastewater(FF), and textile factory wastewater(TF). The results of the RGC mix made with freshwater (FW) has the same amount of wastewater. To investigate the mobility of chloride ions as shown in Figure 2, 36 specimens with dimensions of 100 mm x 100 mm x 100 mm were manufactured. Fifty-four (54) cube samples dimensioned at 100 mm x 100 mm were used to test their resistance to sulphuric acid attack. A mixed GPC design and a WA of RCA were produced, as shown in Table 4.

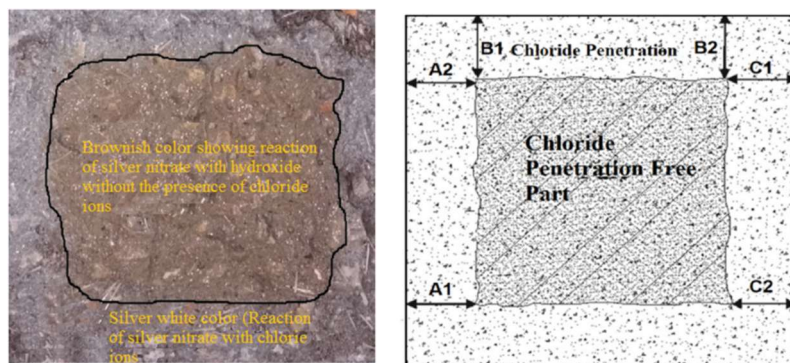


Figure 2. Chloride ion migration test

Table 4. Mix design of RGC

Material	Quantity(kg/m ³)	Material	Quantity(kg/m ³)
Recycled aggregate	1105	Sand	495
Water	125	Superplasticizer	40
Fly ash	245	NaOH solution (14M)	40
GGBS	170	Na ₂ SiO ₃	110

Using a mixer with a volumetric capacity of 0.15 m³ and a speed of 20 revolutions per minute, the concrete was combined in 10 minutes. In order to create a homogenous RGC blend, the aggregates were combined with half of the water during the first sub-period, followed by the remaining water and cement. The mixture was then stirred for five minutes. A workability test for all forms of wastewater was executed in line with ASTM C143 [25], showing results within a span of 85 to 110 mm. Every RGC combination was cured using ordinary water. The four RGC mixes were investigated for chloride ion penetration and acid attack. The specimens were fixed at a standard water temperature for twenty-eight days, dried at 50 °C for 24 hours, and then subjected to an acid assault with 4% H₂SO₄ to test their resistance to sulphuric acid. The specimens were examined for mass loss after being soaked for twenty-eight, ninety, and 120 days. After being analyzed in tap water for twenty-eight and ninety days, the created specimens were oven-dried for twenty-four hours at fifty degrees Celsius to evaluate the penetration of chloride ions. Once the sample had cooled to ambient temperature, it spent fifty-six days in a 4% NaCl solution. After that, the cylinders were divided in half by ASTM C496 [26] and dispersed in water containing a 1.0N AgNO₃ solution. AgNO₃ was reacted with the penetrated chloride ions in a chemical process that produced AgCl, which gave off a silver hue, to evaluate the amount of chloride ions that seep into the concrete cast using the type of wastewater. Based on previous research, this strategy was created [27, 28].

3. Results and Discussions

3.1. Chloride Ion Migration

Consequently, CIM is a critical consideration when evaluating the strength of concrete. Corrosion and oxide formation occurs over the surface of steel bars with increased chloride

concentration. This changes the volume of the material because iron rust is created, and it also speeds up the failure of the concrete cover. When iron in the wastewater oxidizes, the chloride ion (Cl⁻) catalyzes to produce the FeCl₃ complex. This unstable combination reacts with hydroxide ions (OH⁻), producing iron hydroxide (Fe(OH)₂). For free hydroxyl ion absorption, the mixture contains the chloride ion. Because the pH is lowered by the iron hydroxide Fe(OH)₂, chloride ions (Cl⁻) can readily permeate and weaken the oxide layer. In this study, 4% NaCl is used to examine the CIM to concrete. The benchmark utilized to determine this value is penetrated by the specimen chloride ions to a millimeter depth. The values of chloride ion penetration for different RGC mixes are shown in Figure 3. The greatest CIM values were obtained from the FE, which has significant levels of sulphate and chloride ions.

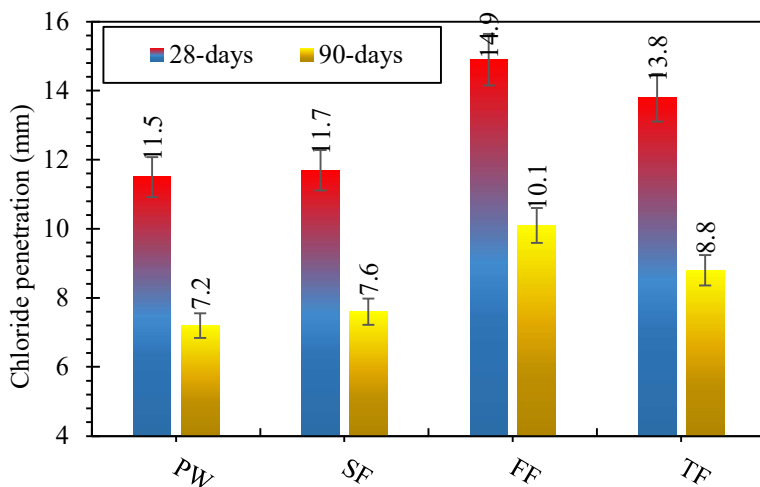


Figure 3. CIM of various RGC mixes

After 28 days, the reference blend's CIM was 11.5 mm, and after 90 days, it was 7.2 mm. The CIM of the TF blend was 16% and 17% higher than FW after twenty-eight and ninety days, respectively. This shows the TF mix is sensitive to steel bar corrosion and oxidation. The FF mix's CIM was 14.9 mm for twenty-eight days and 10.1 mm for ninety days, respectively. The FE accelerates corrosion and faster chloride ion penetration into concrete because of its high chloride and sulfate content [26]. The unusually low pH of the FE blend further increases chloride ion penetration [27]. CSH-gel and fill voids cement matrix and fly ash decrease CIM, resulting in a more compact matrix that prevents CIM from entering the RGC blend. Consequently, the SE demonstrated the least amount of chloride ion penetration of all the wastewater types that were examined, indicating that it is less contaminated.

3.2. Acid Attack Resistance

Due to its alkaline nature, concrete is very prone to acid attacks. These acid attacks cause wastewater to degrade because they occur in the drainage system. As a result, acid resistance becomes a critical criterion of durability that must be monitored. Among all the acids, H₂SO₄ is the most powerful and destructive and has the lowest pH. It efficiently combines with CH to generate CaSO₄, causing the concrete to degrade quickly. The mass reduction of samples

obtained as concrete deterioration at twenty-eight, ninety, and 120 days was investigated in this study. Samples were then submerged in a 4% H_2SO_4 solution. The mass loss incurred by every RGC mixture is displayed in Figure 4. The mix designated as FF saw the greatest decline.

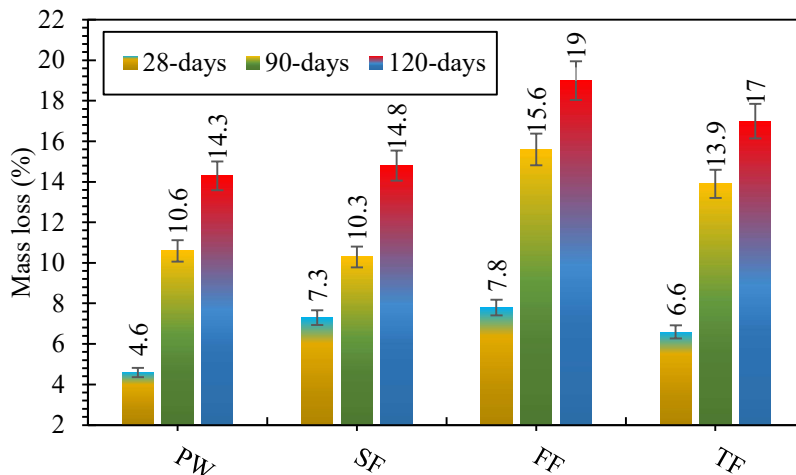


Figure 4. Mass reduction of various RGC blends due to acid attack

When compared to the reference blend, the TF blend deteriorates faster. The TF had mass losses of 6.6% after twenty-eight days, 13.9% after ninety days, and 17% after one hundred and twenty days, 30%, 23%, and 16% higher than the reference blend, respectively. The FF blend had mass losses of 7.8% at twenty-eight days, 15.6% at ninety days, and 19% at 120 days, 40%, 32%, and 24% higher than the reference blend, respectively. The acid's pH value and the wastewater's blending significantly impact concrete deterioration. Also, the sulfate-rich FE could be to blame for the considerable mass loss. The decline of the FF blend was the greatest in the early days, but by 90 and 120 days, it was relatively similar to that of the FW mix. The SF blend suffered higher mass losses due to the H_2SO_4 attack, with losses of 7.3% at twenty-eight days, 10.3% at ninety days, and 14.8% at 120 days, respectively. The comparative mass losses of several concrete mixes at various testing ages as a result of acid assaults are shown in Figure 5. Because FA forms a C-S-H gel following CH and FA particles' pozzolanic activity, it fills up GPC microcracks and reduces the acid absorption of RGC blends [28, 29]. This will decrease H_2SO_4 penetration in RGC, minimizing mass loss at different testing ages.

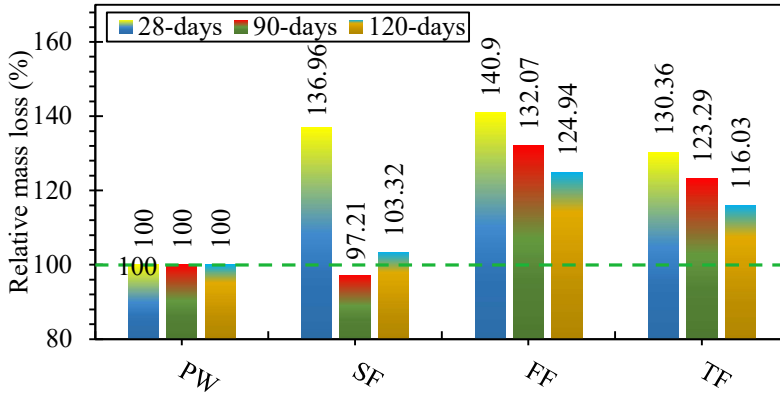


Figure 5. Mass reduction of RGC blends relative to FW RGC mix

3.3. ANOVA Test Results

As shown in Tables 5–6, the significance of variations in RGC blend durability properties after 90 days and mechanical features after 28 days of testing was evaluated in this study using the ANOVA statistical test at a 5% significance level. Each group was given three samples, and the RGC mix was separated into four categories: FF, SF, FW, and TF. A comparison between the RGC blends and the reference blend (FW) was made to illustrate the experimental results' significance accurately. In the ANOVA test with a 95% confidence interval, a P-value less than F_{crit} and more significant than 5% indicate a slight difference in the results of the different RGC mixtures [28, 29]. The CIM results of multiple RGC mixes revealed no significant differences, with an occurrence of 8.84% and $F < F_{crit}$, showing that the influents type tested in RGC blending affects the acid attack results.

Table 5. Results of ANOVA test for CIM of RGC blends

Groups	Count	Sum	Average	Variance		
FW	3	18.2023	6.06746	0.7320		
TF	3	22.1604	7.3868	3.0472		
FF	3	25.4242	8.4747	0.5223		
SF	3	19.1679	6.3893	0.4876		
ANOVA						
SOV	SS	df	MS	F	P-value	F_{crit}
Between Groups	11.4621	3	3.7281	2.9581	0.0839	3.8628
Within Groups	10.1826	8	1.3603			
Total	21.4558	11				

Table 6. Results of the ANOVA test for the sulfuric acid attack of RGC blends

Groups	Count	Sum	Average	Variance		
FW	3	35.3114	11.7704	0.3883		
TF	3	42.0565	14.0188	0.4318		
FF	3	47.0399	15.6799	10.4698		
SF	3	36.5111	12.1703	0.4212		
ANOVA						
SOV	SS	df	MS	F	P-value	F _{crit}
Between Groups	33.0972	3	10.3704	3.3295	0.0636	3.8222
Within Groups	22.9174	8	3.1146			
Total	54.0147	11				

4. Conclusions

This study examined and evaluated the durability properties of geopolymer concrete with recycled aggregate that was produced using various wastewater, including textile, fertilizer, and sugar factories. To determine the significance of the differences in the properties of various recycled concrete aggregate blends, a one-way ANOVA test was utilized. The following important conclusions can be drawn from the experimental findings:

1. Compared to concrete made with fresh water, the CIM tests showed that concrete made with fertilizer industry wastewater had the significant amount of CIM, measuring 14.9 mm at twenty-eight days and 10.1 mm at ninety days. The RGC blends created with textile factory wastewater had the highest CIM of 117% , the blend made with sugar factory wastewater had a higher CIM of 102%, and the RGC mix of SE had the highest CIM of 108% when compared to concrete constructed using fresh water. Because of the high density of GPC, the microstructure of RGC prevented chloride ions from penetrating the cementitious mixture.
2. The RGC blend made using fertilizer factory wastewater had the highest mass loss from acid attack, 19% at 120 days, according to test results exposing the blends to a 4% H₂SO₄ solution. This could be explained by the fertilizer factory wastewater having the lowest pH value, which can be explained by the fact that concrete mass loss rises when pH value decreases. The RGC blend of SE had the most significant mass loss of 112 percent at 120 days, followed by the mix created with textile industry wastewater at 116% and the mix made with sugar factory wastewater at 103% when compared to freshwater concrete. The RGC mixtures demonstrated superior resilience to acid attack due to the dense matrix created by the fine GPC particles.
3. According to the ANOVA test, no discernible variation in CIM or acid attack resistance was seen across the RGC mixes. In conclusion, waste material selection and environmental effects may be used to produce sustainable concrete using the wastewater kinds that have been studied.

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