

Influence of fly ash, glass fibers and wastewater on production of recycled aggregate concrete

✉ A. Raza^a, B. Ali^b, F.U. Haq^c, M. Awais^d, M.S. Jameel^e

a. Department of Civil Engineering, University of Engineering and Technology, (Taxila, Pakistan)
b. Department of Civil Engineering, COMSATS University Islamabad Sahiwal Campus, (Sahiwal, Pakistan)
c. Centre of Excellence in Water Resources Engineering, University of Engineering and Technology, (Lahore, Pakistan)
d. Department of Business Administration, Institute of Southern Punjab, (Multan, Pakistan)
e. Department of Transportation Engineering and Management, University of Engineering and Technology, (Lahore, Pakistan)
✉ aliraza@piet.edu.pk

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ABSTRACT: To encounter the issues of waste materials, low tensile strength of concrete and environmental impacts of cement production, research is needed to develop a sustainable concrete. This study has endeavored to investigate the effects of using recycled coarse aggregates (RCA), various types of wastewater effluents, fly ash, and glass fibers on the mechanical and durability behavior of recycled aggregate concrete (RAC) incorporating with fly ash and glass fibers (FGRAC). Six different kinds of wastewater effluents for the mixing of concrete, 100% replacing the natural coarse aggregates with RCA, and 30% replacement of cement with fly ash were used for the development of concrete. The experimental measurement portrayed that the textile factory effluent presented the highest compressive and tensile strengths of concrete. Fertilizer factory effluent portrayed the highest water absorption, mass loss due to acid attack, and chloride penetration to concrete.

KEYWORDS: Recycled aggregate concrete; Fly ash; Wastewater; Compressive strength; Chloride penetration.

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RESUMEN: *Influencia de las cenizas volantes, las fibras de vidrio y las aguas residuales en la producción de hormigón con árido reciclado.* Para enfrentar los problemas de los materiales de desecho, la baja resistencia a la tracción del hormigón y los impactos ambientales de la producción de cemento, se necesita investigación para desarrollar un hormigón sostenible. Este estudio investiga los efectos del uso de áridos gruesos reciclados (RCA), varios tipos de efluentes de aguas residuales, cenizas volantes y fibras de vidrio sobre el comportamiento mecánico y la durabilidad del hormigón con árido reciclado (RAC), incorporando cenizas volantes y fibras de vidrio (FGRAC). Para el desarrollo del hormigón se utilizaron seis tipos diferentes de efluentes de aguas residuales, se sustituyó el 100% de los áridos gruesos naturales por RCA y el 30% del cemento por cenizas volantes. Se comprobó que el empleo de efluente de fábrica textil promovió la mayor resistencia a la compresión y a la tracción del hormigón. El empleo del efluente de la fábrica de fertilizantes presentó la mayor absorción de agua, pérdida de masa debido al ataque de ácido y penetración de cloruro en el hormigón.

PALABRAS CLAVE: Hormigón con árido reciclado; Cenizas volantes; Aguas residuales; Resistencia a compresión; Penetración de cloruros.

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1. INTRODUCTION

The construction industry is generating a large quantity of construction and demolishing waste in the form of concrete waste which needs to be properly managed for sustainable development. The application of concrete waste in the form of recycled aggregate concrete (RAC) minimizes the requirement of landfills for the demolition waste, and transportation costs of aggregates by preserving the natural resources, reclamation lands, and reducing the number of loads headed to landfills (1-6). Furthermore, the production of cement is increasing to meet the demand for concrete construction resulting in high carbon dioxide emissions. The impact of cement on the environment can be minimized by partially replacing it with fly ash. Additionally, a large portion of industrial and municipal wastewater is discharged into rivers and landfill sites. The environmental regulating agencies are following strict guidelines and denying a municipal landfill near cities. These agencies are enforcing pressure to identify an alternative way of disposal at a fair price. The rapid development in population and the increase in economic developments raised the demand for freshwater. Concrete requires one trillion gallons of water annually which is the second largest used material after water (7). Hence, the use of freshwater in construction industries and other sectors must be reduced to build an equilibrium between the demand and supply of freshwater (8). The half population of the world will be faced with a shortage of freshwater by 2025 (9). Researchers are emphasizing to reuse of wastewater, especially in concrete production. The wastewater can be used in the construction of concrete to minimize the high cost of its management (10).

It was concluded that RAC-produced concrete exhibits inferior characteristics as compared to traditional concrete (5, 11-14). Some findings indicate that when recycled coarse aggregate (RCA) is used as a substitute to natural coarse aggregate (NCA) then the compressive strength of concrete is reduced between 20 to 30% (15-17). Besides, the compressive strength is reduced by 20 to 25% when NCA is fully replaced with RCA by holding the quantity of cement and W/C ratio constant (18). When RCA is collected from different resources, the difference in compressive strength is more pronounced due to the variance of aggregate properties (18-25). The mortar stuck with coarse aggregate often compromises the strength properties of recycled aggregate concrete (RAC). If 34% mortar is stuck to an aggregate of size 10 to 20 mm then the compressive strength of RAC is reduced up to 10% (22). In the first 180 days, concrete produced with biologically treated wastewater reported a 17% improvement in compressive strength. Afterward, axial strength in the case of secondary treated wastewater tends to decrease by approximately 18% relative to primary treated wastewater. However, the water ab-

sorption is higher, when secondary treated wastewater is used in concrete production (26).

After examining the behavior of concrete fabricated with cementitious wash water, Asadollahfardi *et al.* (27) reported that cement wash water can be successfully used for the production of good quality fresh concrete. Experimental results showed that concrete fabricated with cement wash water or a mixture of it and clean water was performed better as compared to that concrete developed with silica and water admixture (28). Another research conducted by Wasserman (29) found that the compressive strength of concrete enhanced when cementitious washout water is used in concrete production as compared to traditional concrete. The compression performance of concrete was explored by using three kinds of wastewater such as sewage water, groundwater, and potable water, Nikhil *et al.* (30) deduced that concrete showed maximum compressive strength when drinking water used. Rabie *et al.* (31) performed an experimental study on mechanical properties of concrete developed by using wet and dry sewage sludge observed that there was a minor difference in compressive strength values by replacing cement content with wastewater sludge at 5%, 10%, and 15% (by weight of cement content), but compressive strength beyond that percentage tends to decrease by 61.6% and 68.5%, correspondingly. Roychand *et al.* (32) investigated the mechanical performance of concrete developed by using steel slag collected from civic wastewater effluent plant and reported that after substituting the coarse aggregate with steel slag aggregate, the compressive capacity increased by 18% and 16.8% at 7 and 28-days curing, correspondingly. Research conducted by Saxena and Tembhurkar (33) reported that bio-concrete showed a decline in its properties by incorporating wastewater and steel slag which can be fixed by using microbiologically induced CaCO_3 . The tensile and compressive strength of bio-concrete was increased by 12.5% and 31.1% due to its reduced water absorption.

Many studies explore the performance of RAC with fly ash (34-40). These investigations depicted that the effect of fly ash in RAC was superior to that in natural aggregate concrete (NAC). Kurad *et al.* (41) studied the effect of replacing NCA with RCA and cement with fly ash. They concluded that the compressive strength of concrete decreased up to 3% when RCA was 100% replaced with RAC. 30% replacement of cement with fly ash reduced the strength of concrete up to 4%. Moreover, the decrease in the compressive strength of concrete for the combined use of RCA and fly ash was less than their individual use due to the pozzolanic reaction of fly ash with the adhered cement paste of RCA. Some studies (34, 35, 38, 42) portrayed that the incorporation of fly ash to the RAC presented better performance as compared with NAC in terms of sorptivity,

chloride ion migration, and water absorption, etc. The addition of glass fibers improved the compressive, split tensile, and flexural strengths of concrete due to the enhanced bridging effect of fibers in concrete (43-48). Xue et al. (49) explored the bonding behavior between the steel fibers and RAC manufactured with mineral admixtures (silica fume) and observed an improvement in the compressive strength of RAC due to a good bond between steel fibers and RAC. Furthermore, the incorporation of both silica fume and steel fibers significantly improved the performance of RAC at elevated temperatures.

1.1. Scope and significance

The contaminated wastewater is producing negative impacts on the natural atmosphere as well as on human health. Therefore, such adverse impacts on the environment and human health could be avoided up to a certain limit by using wastewater in the concrete mix. Furthermore, to overwhelm the low tensile strength of plain concrete and the high carbon footprint of the cement industry, the use of glass fibers and fly ash to concrete is beneficial. In this study, mechanical properties such as compressive strength and split tensile strength as well as durability properties i.e., water absorption, chloride penetration, and resistance against H_2SO_4 of the recycled aggregate concrete incorporating with fly ash and glass fibers (FGRAC) have been studied under different curing ages by employing six types of wastewater for mixing purpose such as domestic sewage wastewater (DSW), fertilizer factory wastewater (FFW), textile factory wastewater (TFW), sugar factory wastewater (SFW), leather factory wastewater (LFW), and service station wastewater (SSW). One concrete mix was manufactured with potable water without adding glass fibers and fly ash for the comparative analysis. A one-way variance analysis (ANOVA) study was conducted at the five percent significance level to determine the value of discrepancy between the different properties

of FGRAC mixes.

2. TESTING PROGRAM

2.1. Materials

Ordinary Portland cement having grade 43 was employed for concrete production as per ASTM C150/C150M (50). The physicochemical properties of cement are presented in Table 1. F type fly ash taken from DIRK Pozzoplast was used in the present study. The chemical and physical properties of fly ash were reported in Table 1. The RCA was used by replacing 100% NCA. For this purpose, reinforced concrete columns and cylinders with ages of 1 to 2 years were crushed having a compressive strength ranging between 30 MPa and 45 MPa. The recycled aggregate with a maximum size of 12 mm was obtained. In this study, Lawrancepur sand was used according to ASTM C33/C33M-18 (51). The physical and chemical properties of sand and RCA are mentioned in Table 2 and the sieves analysis graphs of both materials are presented in Figure 1. The alkali-resistant glass fibers were employed in the present study having a tensile strength of 1800 MPa and a specific gravity of 2.65. Some of the main characteristics of glass fibers were reported in Table 3. The RAC was manufactured with six various types of wastewater based on their origins and potable water. The clean water was fully relieved by each wastewater type. The chemical examination of each type of wastewater was carefully performed and mentioned in Table 4. Besides, the chemical properties of wastewater were comprehensively tested in the Pakistan Council of Research in Water Resources.

2.2. Fabrication and testing of specimens

To achieve an optimal saturation, the RCA was submerged in potable water for 10 minutes (58). Seven

TABLE 1. Chemical and physical features of cement.

Physical properties		Chemical properties			
Parameter	Cement	Fly ash	Component	Cement	Fly ash
Consistency (%) (52)	29.2	28.6	SiO ₂ (%)	22.3	60.4
Specific gravity (53)	3.0	2.3	Al ₂ O ₃ (%)	5.7	26.7
Final setting time (mins) (54)	235	-	SO ₃ (%)	2.5	1.1
Initial setting time (mins) (54)	110	-	MgO (%)	5.3	0.8
Specific surface area (m ² /kg) (55)	330	423	CaO (%)	59	4.2
Fineness (Blaine Test) (cm ² /g)	2770	2950	Fe ₂ O ₃ (%)	6.0	2.5
Compressive strength at 3 days (MPa) (56)	38.5	-	Loss of ignition (%)	2.9	4.2
Compressive strength at 28-days (MPa) (56)	42.5	-	K ₂ O (%)	0.8	-
Soundness (57)	No expansion	-	Na ₂ O	0.4%	1.4

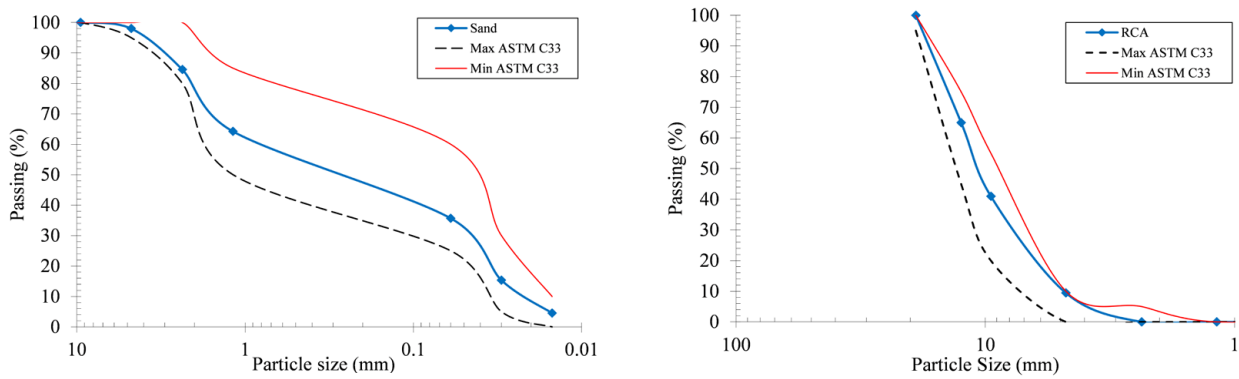


FIGURE 1. Granulometry of aggregates (left) fine aggregates (right) coarse aggregates.

TABLE 2. Various features of RCA and sand.

Property	Sand	RCA
Water absorption after one day (%)	2.25	7.7
Fineness modulus	2.45	-
Specific gravity	2.62	2.25
Dry density (kg/m ³)	1650	1305
Maximum size (mm)	4.75	12.0
Minimum size (mm)	-	4.75

TABLE 3. Characteristics of glass fibers.

Parameter	Value	Parameter	Value
Diameter (mm)	15	Length (mm)	8-16
Melting point (°C)	1000	Texture (g/km)	80
Loss on ignition at 900°C (%)	1.15	Moisture (%)	0.4
Elastic modulus (GPa)	70	Tensile strength (MPa)	1800
Specific gravity	2.65	Density (kg/m ³)	890

TABLE 4. Properties of different types of wastewater considered in the present work.

Parameter (unit)	PW	FFW	TFW	SSW	DSW	SFW	LFW
pH value	7.0	2.5	7.2	6.0	7.4	7.5	6.5
TDS (mg/l)	761.6	2138	325.6	416.5	931.6	2712.2	387
TSS (mg/l)	26.4	47.6	18.7	59.5	433.5	58.7	35.2
Turbidity (NTU)	0.8	2.8	1.0	31.5	212.5	21.3	22.6
DO (mg/l)	5.4	2	4.5	2.2	2.4	2.6	5.3
COD (mg/l)	15.8	488.3	102	1207	357.9	807.5	1075
BOD (mg/l)	10.4	518.5	59.5	952	264.4	612	852
Alkalinity (mg/l)	69.8	1.4	40.8	73.1	82.5	104.6	23.5
Conductivity (m-s/cm)	1.2	7.3	0.6	0.7	1.6	5.7	1.4
Bicarbonates (mg/l)	283.1	180	10.8	297.5	340	637.5	14.3
Hardness (mg/l)	307.7	2176	290.7	314.5	612.9	1802	225.4
Sulphate (mg/l)	6.2	807.5	89.3	98.6	641.8	178.5	74.6
Fluoride (mg/l)	0.3	0.1	0.6	0.1	1	0.4	0.5
Nitrate (mg/l)	1.2	56.1	2.4	8.5	86.7	27.2	2.2
Chloride (mg/l)	10.4	892.5	53.9	212.5	289	732.7	183.4
Iron (mg/l)	1.7	3.1	0.8	1.0	0.7	1.3	1.2

TABLE 5. Quantities of different ingredients of various FGRAC mixes.

Mix ID	Mixing water		Cement (kg/m ³)	Fly ash (kg/m ³)	Glass fibers (kg/m ³)	RCA (kg/m ³)	Sand (kg/m ³)
	Type	Content (kg/m ³)					
PW30-GF-100RCA	Potable water	233	466	94	12	1050	625
DS30-GF-100RCA	Domestic sewage	233	372	94	12	1050	625
FF30-GF-100RCA	Fertilizer factory	233	372	94	12	1050	625
TF30-GF-100RCA	Textile factory	233	372	94	12	1050	625
SF30-GF-100RCA	Sugar factory	233	372	94	12	1050	625
SS30-GF-100RCA	Service station	233	372	94	12	1050	625
LF30-GF-100RCA	leather factory	233	372	94	12	1050	625

different types of FGRAC mixes i.e., potable drinking water mix (PW30-GF-100RCA), domestic sewage wastewater mix (DS30-GF-100RCA), fertilizer factory wastewater mix (FF30-GF-100RCA), textile factory wastewater mix (TF30-GF-100RCA), sugar factory wastewater mix (SF30-GF-100RCA), service station wastewater mix (SS30-GF-100RCA), and leather factory wastewater mix (LF30-GF-100RCA) were prepared. For comparative analysis, each of the FGRAC mixes was compared with the FGRAC mix prepared using potable water (PW) containing fly ash and glass fibers. The labeling of FGRAC mixes was done in such a way that the first two letters from the left side indicate the type of wastewater, the first digit from the left side indicates the percentage of fly ash, two letters at the middle indicate the addition of glass fibers, the digit from the right side indicates the 100% replacement of NCA with RCA, and three letters at the right side indicate recycled aggregate concrete (RAC).

A total of twenty-one cylindrical specimens (150 mm 300 mm) from each wastewater (constant quantity) were prepared for the determination of compressive strength and splitting tensile strength. Three samples for each wastewater at all ages were prepared and tested. A total of forty-two specimens (50 mm height and 100 mm in diameter) were developed for examining the water absorption. For the determination of chloride ion migration, forty-two samples (100 mm in diameter and 100 mm in height) were also prepared. Whereas, sixty-three cube samples of size 100 mm were cast to explore the resistance of FGRAC concrete against sulfuric acid attack. The ingredients and quantities utilized for each FGRAC blend as shown in Table 5.

A mixer at a speed of 20 revolutions/min (capacity of 0.15 m³) was used to mix concrete. A total of 10 minutes required for complete mixing. To achieve a homogenous mixture, the aggregate was mixed with water, fly ash, and cement in the first 5 minutes then added the remaining quantity of water and the glass fibers. For each wastewater mix, a slump test (as per ASTM/C143) was performed and its values ranging between 90 mm to 105 mm (59). For curing purposes, normal water was used in this study.

The properties such as compressive strength and split tensile strength for each RAC blend at different curing ages were tested. The compressive strength of specimens at 7, 28, and 90-days was tested according to ASTM C39 (60). On the other hand, the split tensile strength of specimens at 28 and 90-days was tested as per ASTM C496 (61). The strength properties such as chloride ion migration, water absorption, and acid attack were tested for all seven FGRAC blends. For the determination of water absorption, ASTM C1585 (62) was followed. All specimens at 28-days were placed at room temperature to find resistance against sulfuric acid (H₂SO₄) left to dry at 50 C° for 24 hours then immersing them in 4% H₂SO₄.

To find out how chloride ion penetrates, the specimens developed have been cured in water for 28 and 90-days, preceded by oven-drying at a temperature of 50°C for 24 hours. Following this, the specimens were cooled to normal temperature and then submerged in a solution of 4% NaCl for 56 days. The splitting of cylinders procedure was followed as per the ASTM C496 (61) and spraying with a 1N AgNO₃ solution into water. When AgNO₃ reacts chemically with chloride ions, AgCl is produced giving a silver color.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Compressive strength

In this current investigation, the compressive strength for each of the six different FGRAC mixes was tested after 7, 28, and 90-days of curing as per ASTM C39 (60). Figure 2 reports the compressive strength of each varying FGRAC mix. Three developed samples of all RAC blends for each age group were placed compression test machine then their mean results were calculated. TF30-GF-100RCA mix recorded the maximum compressive strength while the DS30-GF-100RCA mix displayed the lowest compressive strength at all the various testing ages. A control mix (PW30-GF-100RCA) has been developed to conduct a

relative study of the results of different FGRAC mixtures produced using different kinds of wastewater. At 7-days, the compressive strength shown by PW30-GF-100RCA was 18.45 MPa. The compressive strength at 28-days was 26 MPa which was improved by 29% when compared with the measurement at 7-days. The compressive strength was 31.36 MPa when checked at 90-days, which was 142% of the compressive strength observed at 7-days. Thus, the PW30-GF-100RCA mix with the testing age noted a significant rise in its compressive strength.

The compressive strength of concrete for the TF30-GF-100RCA mix improved dramatically when compared with PW30-GF-100RCA at all ages. At 7-days, the TF30-GF-100RCA blend showed a compressive strength of 22.4 MPa which was 17.6% higher as compared to the compressive strength of PW30-GF-100RCA at 7-days. After 28-days, the compressive strength of the TF30-GF-100RCA mix was increased by 135% having a value of 34.6 MPa which was 24.8% higher as compared to the compressive strength of the PW30-GF-100RCA mix. When bicarbonates and fluoride existing in TFW involves a reaction with Al_2O_3 remaining in ordinary Portland cement and thus proceed to calcium fluoroaluminate formation leading to the increased compressive strength of concrete. This mineral is extremely toxic, resulting in both fast setting and early hydration, which improved the performance (33). The high compressive strength of TF30-GF-100RCA than the control mix may also be ascribed to the addition of glass fibers and fly ash. Fly ash reduces the voids between fine particles and form CSH-gel after the chemical reaction of free CH and fly ash particles. Furthermore, the glass fibers provided the bridging effects between the particles of the TF30-GF-100RCA mix to improve the compressive strength.

The improved compressive strengths of FGRAC mixes developed with wastewater could be ascribed to the pozzolanic reactions between free fly ash and CH. Fly ash filled the voids between sand and cement, improved the bond of glass fibers with the binding matrix, and, finally, formed a gel (C-S-H-gel) giving a stronger bond. Furthermore, the ability of glass fibers to prevent the propagation of cracks also improved the compressive strength of FGRAC mixes to give comparable results with the control mix.

By using FFW to produce FGRAC mixes, the compressive strength attained at 7-days was higher and lesser at 28 and 90-days associated with PW30-GF-100RCA. At 7-days, the FF30-GF-100RCA mix exhibited a compressive strength of 21.2 MPa that is 13% higher than the compressive strength of PW30-GF-100RCA at 7-days. The compressive strength of the FF30-GF-100RCA mix was increased by 15.6% at 28-days having a value of 25.2 MPa. It was further decreased by 7.8% at 90-days when compared with PW30-GF-100RCA but it showed 12.9% higher strength than at 28-days. This drop in the compressive strength of FF30-GF-100RCA mix at 28 and 90-days

of testing occurred because of an increased quantity of COD as well as BOD at 5-days in FFW (63).

When DSW has been used for mixing, the compressive strength of concrete decreased considerably. At 7-day testing, the compressive strength was observed 11.9 MPa, at 28-days testing it was 18 MPa, and at 90-day testing, it was 15.3 MPa. The average compressive strengths were 35%, 30%, and 51% lower than the strengths reported in the same order by the PW30-GF-100RCA mix at testing days of 7, 28, and 90. The uniformity of the mixing water has a significant effect on concrete strength. Consequently, the concrete strength for DS30-GF-100RCA is lower than PW30-GF-100RCA. While at 28-days of testing, this strength of the DS30-GF-100RCA mix increased to 34.3% and it shows a reduction of up to 15% at testing days of 90. This reduction in the strength of the DS30-GF-100RCA mix can be due to the existence of many organic matters in DSW that reacts with cement ingredients and thus result in reducing the strength of concrete. Due to the large amount of sulfate found in DSW, the compressive strength of the DS30-GF-100RCA mix is decreased after 90-days of testing.

When SSW was used for mixing, then the compression capacity of concrete was affected to a slight extent. It had shown compressive strengths of 16.9 MPa in 7-days, 23.9 MPa in 28-days, and 29.8 MPa in 90 test days. These compressive strengths were in similar accordance with that of the PW30-GF-100RCA mix and on average 8.4%, 8%, and 4.8% were lower than compressive strengths displayed by the PW30-GF-100RCA mix at the testing days of 7, 28, and 90. These negligible variations indicate that the concrete compressive strength has no noticeable effect when SSW is used for mixing. The reason is that SS30-GF-100RCA has shown a decline in strength at all test ages which can be due to the existence of BOD and COD in excessive amounts. The concrete compressive strength decreased at 7-days by using SFW comparison to the PW30-GF-100RCA mix, which subsequently increased to 43.9% after 28-day testing. SF30-GF-100RCA mix has shown increased strength because of the long setting time of cement paste and the larger surface area of cement particles (64). Compared with the PW30-GF-100RCA mix, the concrete compressive strength decreased by 5% at 90-days. This drop in the compression capacity can be due to the availability of C_3S in cement triggering the hydration process to delay (65, 66). Figure 3 represents the comparative strengths of all RAC blends at 7, 28, and 90 test days.

When LFW was used for mixing, then the compression capacity of concrete was affected to a slight extent. It had shown compressive strengths of 16.7 MPa in 7-days, 29.9 MPa in 28-days, and 30.5 MPa in 90 test days. These compressive strengths were in similar accordance with that of the PW30-GF-100RCA mix and on average 9.5%, 3.3%, and 7% lower than compressive strengths displayed by the PW30-GF-100RCA mix at the testing days of 7, 28, and 90. These

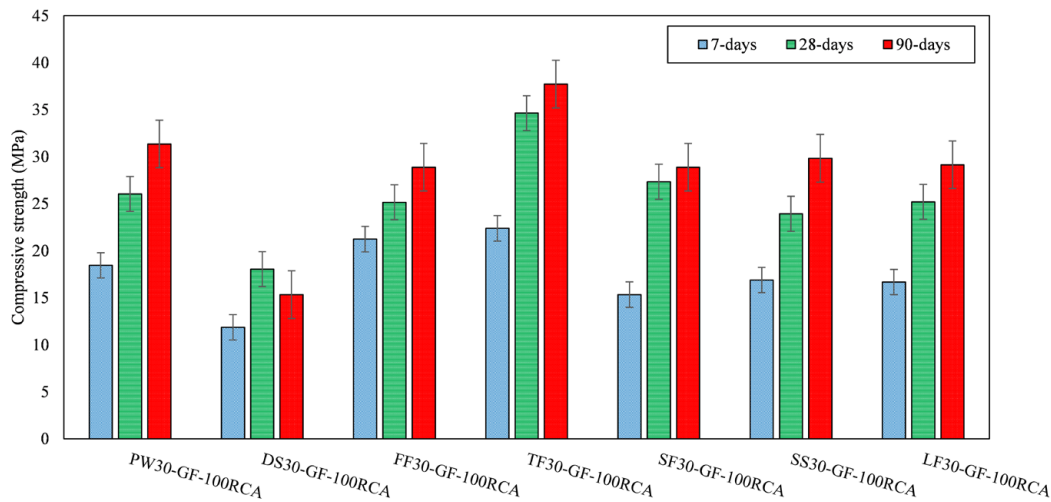


FIGURE 2. Compressive strengths of FGRAC mix at 7, 28, and 90-days.

negligible variations indicate that the concrete compressive strength has no noticeable effect when LFW is used for mixing. The reason is that LF30-GF-100RCA has shown a decline in strength at all test ages that may be associated with a large amount of COD and BOD in LFW. The improved compressive strengths of FGRAC mixes fabricated with wastewater could be ascribed to the pozzolanic reactions between free CH and fly ash. Fly ash filled the voids between sand and cement, improved the bond of glass fibers with the binding matrix, and, finally, formed a gel (CSH-gel) giving a stronger bond. Furthermore, the ability of glass fibers to prevent the propagation of cracks also improved the compressive strength of FGRAC mixes to give comparable results with the control mix.

3.2. Split tensile strength

Figure 4 demonstrates the split tensile behavior of various FGRAC mixes that have been manufactured using different wastewater types. The specimens were tested following ASTM C496 (61). The PW30-GF-100RCA mix displayed an average tensile strength of 2.45 MPa at 7-days, 2.85 MPa at 28-days, and 3.46 MPa at 90-days, respectively indicating that the PW30-GF-100RCA mix displayed a split tensile strength of 117% at 90-days compared to its strength at 28-days. The TF30-GF-100RCA mix showed significantly higher split tensile strength whereas the DS30-GF-100RCA mix showed the lowest strength. The TF30-GF-100RCA mix displayed improved split tensile strengths of 2.84 MPa after 7-days, 3.6 MPa after 28-days and 4.1 MPa at 90-days that were 13.7%, 20.8%, and 15.6% greater than the PW30-GF-100RCA mix tested at various days, respectively. The tensile strength displayed by the TF30-GF-100RCA mix was greater as the TFW has lesser bicarbonates amounts relative to other wastewater types. After all, the rise in bicarbon-

ates contributes to reduced tensile strength (67). The improved split tensile behavior of FGRAC mixes may be attributed to the pozzolanic reactions between free fly ash and CH. Fly ash forms the C-S-H-gel and fills the small voids between the fine aggregates and binder particles. Furthermore, the ability of glass fibers to prevent the propagation of cracks and to produce the bridging effect also improved the split tensile strength of FGRAC mixes to give comparable results with the control mix PW30-GF-100RCA.

The FF30-GF-100RCA mix indicated split tensile strengths of 2.36 MPa at 7-days, 2.68 MPa at 28-days, and 3.17 MPa at 90-days, respectively. This indicates that the split tensile strengths were reduced by 3.6% at 7-days, by 5.9% at 28-days, and by 8.4% at 90-days associated with the control mix when FFW was used for mixing. The tensile strengths demonstrated by the DS30-GF-100RCA mix were small with falls of 8.9% at 7-days, 7% at 28-days, and 9.8% at 90-days as compared with the PW30-GF-100RCA mix. The SF30-GF-100RCA mix displayed split tensile strengths of 2.34 MPa at 7-days, 2.71 MPa at 28-days, and 3.29 MPa at 90-days with a reduction of 4.5% at 7-days, 5.0% at 28-days, and 4.8% at 90-days, respectively. The decreases in split tensile strengths displayed by diverse FGRAC mixes (i.e. FF30-GF-100RCA, DS30-GF-100RCA, SS30-GF-100RCA, and SF30-GF-100RCA) can be due to the excess of total suspended solids, COD, and BOD in such kinds of wastewater (68). The concrete displays a reduction in the tensile strength when the volume of chloride increases (69). This is due to the presence of large quantities of chloride. These FGRAC mixes have lower pH values. The reduction of the pH value is responsible for reducing the strength of the split tensile (70).

Figure 5 shows the comparison between the relative percentage of split tensile strengths produced by various FGRAC mixes and that reported by the PW30-GF-

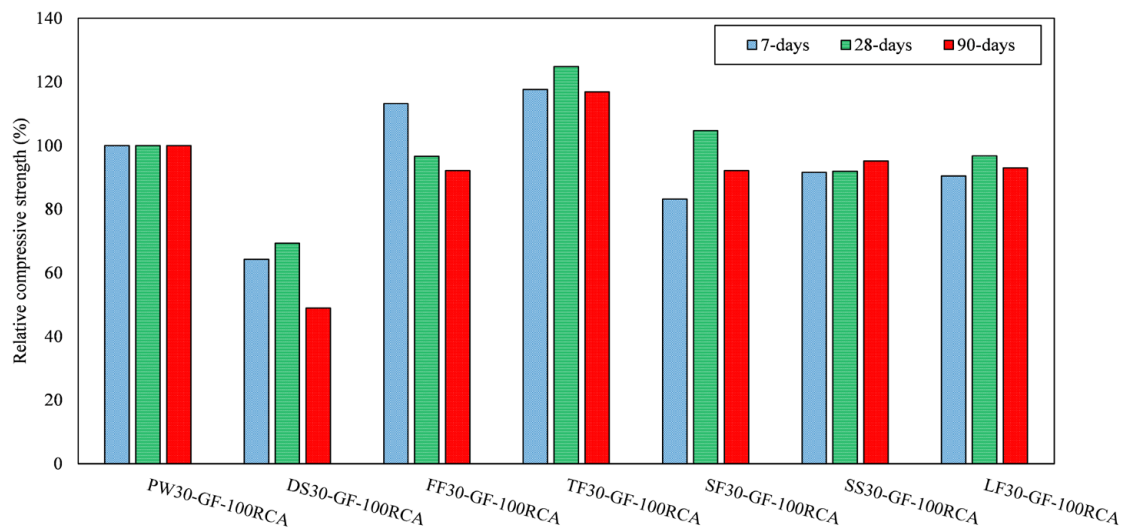


FIGURE 3. Relative comparative compressive strengths of FGRAC mix at 7, 28, and 90-days compared with control mix.

100RCA mix for different age groups. The LF30-GF-100RCA mix displayed enhanced split tensile strengths of 2.89 MPa after 7-days, 3 MPa after 28-days, and 3.4 MPa at 90-days that were on average 15.2% and 5.6% greater than the PW30-GF-100RCA mix experienced at 7 and 28-days, respectively. While this mix presented a 2% lower value of split tensile strength at 90-days compared with the PW30-GF-100RCA mix. The tensile strength displayed by the LF30-GF-100RCA mix was greater as the LFW has lesser bicarbonates amounts relative to other wastewater types because the rise in bicarbonates results in the reduced tensile behavior of concrete (67).

3.3. Water absorption

Being a durability parameter, the water absorption

calculates the number of pores that are moisture-accessible in concrete. If water absorption is extreme, it will cause reinforcement corrosion which leads to the penetration of numerous toxic chemicals and when react with cement additives thus completely change the characteristics of concrete. Figure 6 indicates the water absorption shown by different RAC blends. Nearly all the specimens displayed relatively higher water absorption levels. This may be due to higher water absorption levels for RCA (7.7%). When the findings were analyzed, they demonstrated that the different types of wastewater had no significant impact on concrete water absorption as shown in the literary works (71).

Different FGRAC mixes reported a reduction in the properties of water absorption with time. The water absorption shown by the PW30-GF-100RCA mix

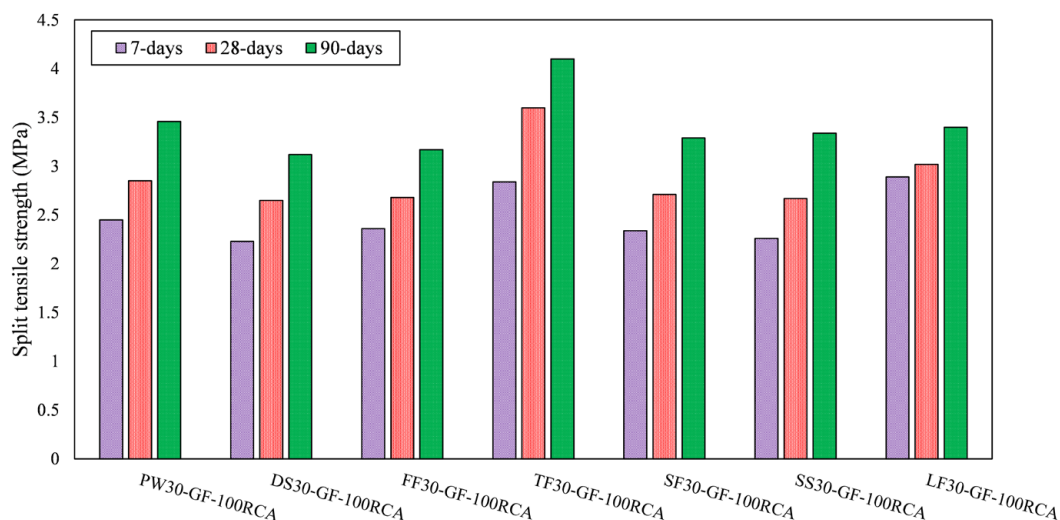


FIGURE 4. Split tensile strength of FGRAC mixes at 7, 28, and 90-days.

was 12.5% at 28-days and 9.2% at 90-days, representing the decline in moisture content over time. As compared to PW30-GF-100RCA, the water absorption shown by the TF30-GF-100RCA mix was lower. The moisture content was 99% at 28-days and 98% at 90-days equated to PW30-GF-100RCA. The decline in water absorption may be attributed to a reduction in the amount of chloride, as the volume of chloride rises, the concrete density lessens with reduced strengths plus enhanced porosity in concrete (69).

When tested at 28 and 90-days, correspondingly, the water absorption values of the FF30-GF-100RCA mix were 9.7% and 16.5% higher than that of PW30-GF-100RCA. The DS30-GF-100RCA mix displayed moisture content that is the highest with 14.6% at 28-days, 12% at 90-days that have been 14.7%, and 23.9% higher than with the PW30-GF-100RCA mix. The large quantities of organic wastewater existing in DSW contribute to the establishment of large numbers of small pores resulting in higher water absorption. The water is consumed by such waste during the mixing process and then emitted during concrete casting, which increases the ratio of water to cement (W/C) and thus decreases the concrete density (72). When tested at 28 and 90-days correspondingly, the water absorption values of the SS30-GF-100RCA mix were 8% and 22.8% higher than PW30-GF-100RCA. Water absorption was enhanced by 11% at 28-days, and by 17% at 90-days while mixing with SFW. While using LFW in the mixing of concrete, water absorption enhanced by 6.5% and 11.7% at 28 and 90-days, respectively as related to the control mix. As previous studies have shown, water absorption has been increased by using various forms of wastewater in concrete mixes (33). The reduced water absorptions of FGRAC mixes may be attributed to the reason that the addition of fly ash helps to reduce the water absorption of concrete by filling the voids between the

fine aggregates and the binder matrix but the addition of glass fibers and the use of RCA increases the water absorption due to high water absorption of RCA and the enhancement in the length of microchannels in the microstructure of concrete (44).

3.4. Chloride penetration

In this study, chloride penetration of concrete is studied using 4% NaCl. The method used to calculate this parameter is the penetration of ions color in millimeters penetrated by the chloride ions into the concrete microstructure. Figure 7 indicates the values of chloride ions penetration for all types of FGRAC mixes. The highest chloride penetration values were given by the FFW, which is rich in chloride iron and sulfate ions.

The control mix portrayed a chloride penetration of 11.87 mm at 28-days, and 7.45 mm at 90-days. At 28 and 90-days, the TF30-GF-100RCA mix displayed chloride penetration that was 12.6% higher and 18.9% higher than PW30-GF-100RCA. This depicts the TF30-GF-100RCA mix as more vulnerable to oxidation and steel bar corrosion. Also, penetration of chloride indicated by the FF30-GF-100RCA blend was 14.23 mm in 28-days and 10.41 mm in 90-days. Chloride ion penetration is also enhanced by the pretty low pH value of FFW (70). The increased values of chloride penetration to FGRAC mixes may be ascribed to the high water absorption of RCA and the addition of glass fibers causing a balling and bridging effect between the binder matrix leaving more voids to absorb chloride ions. But the addition of fly ash is advantageous to resist the penetration of chloride ions by filling the microstructure of concrete.

Fewer iron quantities in the DSW resulted in the chloride penetration values being close to the control mix. The chloride penetration shown by the SS30-GF-

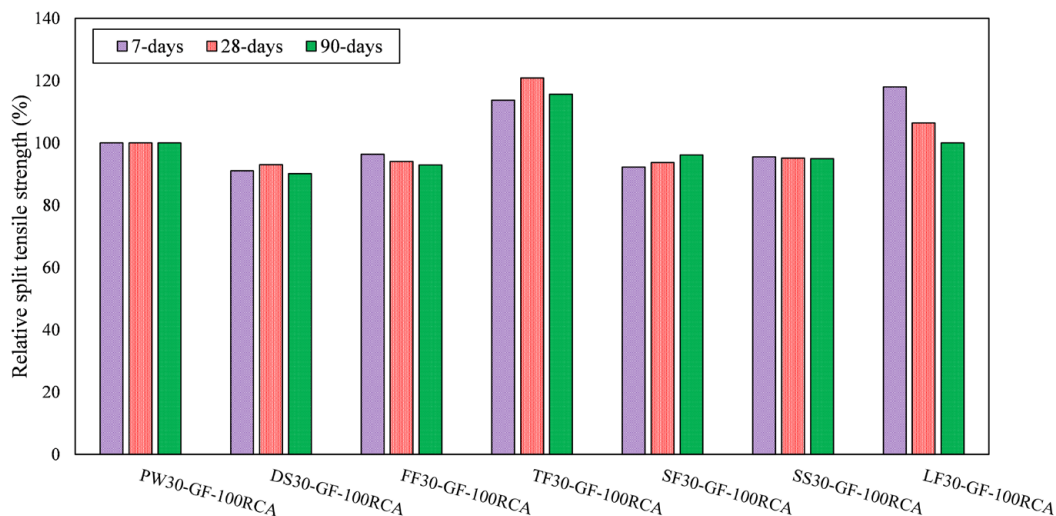


FIGURE 5. Relative split tensile strengths of FGRAC mix at 7, 28, and 90-days.

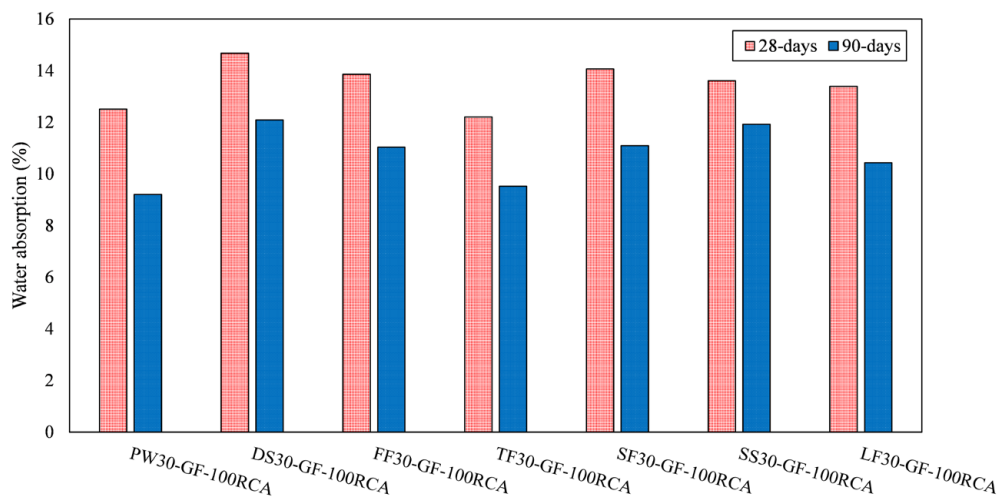


FIGURE 6. Water absorption of FGRAC mixes at 28 and 90-days.

100RCA blend was 13.37 mm and 9 mm at 28- and 90-days, which is 11.2% and 17.2% higher on average than PW30-GF-100RCA values. The SF30-GF-100RCA mix demonstrated chloride penetration values close to those of the SS30-GF-100RCA mix. Similarly, the LF30-GF-100RCA mix depicted higher values of chloride ion penetration (12.24 mm at 28-days and 9.64 mm at 90-days) that were 3% and 22.7% higher than the control mix at 28 and 90-days, respectively. Hence, the chloride ion penetration represented by DSW was the lowest from all forms of wastewater tested, which indicates that it is less prone to corrosion.

3.5. Acid attack resistance

This study examined the mass loss of test samples at 28, 90, and 120-days after soaking them in 4% of the H_2SO_4 solution. Figure 8 indicates the mass losses caused by each of the FGRAC mixes. The highest degradation was observed by the FF30-GF-100RCA mix.

The degradation of the TF30-GF-100RCA mix is quicker than the control mix. TF30-GF-100RCA mix reported mass losses of 6.28% after 28-days, 13.11% after 90-days, and 16% after 120-days, which were 30.2%, 23.3%, and 15.8% higher than the PW30-GF-100RCA mix. The FF30-GF-100RCA mix reported mass losses of 7.3% at 28-days, 14.89% at 90-days, and 17.86% at 120-days that were 40%, 32.5%, and 24.5% higher than the PW30-GF-100RCA mix. The largest mass loss of the FF30-GF-100RCA mix can be linked to the lowest pH value (73, 74). Concrete deterioration is thus largely influenced by the pH value of both acid and wastewater mixing (75). Also, the greater mass loss can be due to the sulfate-rich FFW. The DS30-GF-100RCA mix exhibited higher degradation in the initial stages, but the degradation became identical to that of PW30-GF-100RCA at 90 and 120-days. The SF30-GF-100RCA mix displayed mass losses of 5.2% at 28-days, 12% at 90-days, and 15.4%

at 120-day testing that were higher due to the sulfuric acid (H_2SO_4) invasion. The mass loss of LF30-GF-100RCA was observed to be 5.2%, 11%, and 14.4% at 28, 90, and 120-days, correspondingly. These mass losses were 15.6%, 9.2%, and 6.1% higher than that of the PW30-GF-100RCA mix. So, we can say that with the use of all the various forms of wastewater examined, the degradation of concrete becomes more rapid. Figure 9 records the relative mass losses of diverse concrete mixes at various testing ages due to an acid attack as compared with the control mix. The increased values of mass losses of FGRAC mixes may be attributed to the addition of glass fibers causing a bridging effect between the binder matrix leaving more voids to absorb chloride ions. But the addition of fly ash is advantageous to resist the acid attack by filling the microstructure of concrete.

3.6. Statistical analysis

Tables 6-10 demonstrate the ANOVA analysis at a significance level of 5% used to assess the importance of the discrepancies between the various durability properties of the FGRAC mixes at 90-days and the mechanical behavior at 28 testing days. The FGRAC mix was split into six groups of wastewater concrete mixes (TF30-GF-100RCA, FF30-GF-100RCA, DS30-GF-100RCA, SS30-GF-100RCA, SF30-GF-100RCA, and LF30-GF-100RCA) and a control mix PW30-GF-100RCA. A comparison was made between FGRAC mixes and the control mix (PW30-GF-100RCA) to explain the impact of the experimental outputs precisely.

The findings of the ANOVA test indicate that different FGRAC mixes did not show a substantial difference at 28-days of testing ($P = 32.9\%$ and $F < F_{crit}$) between their compressive strengths at 28-days of testing, showing that the types of wastewater tested directly did not influence the compressive strength

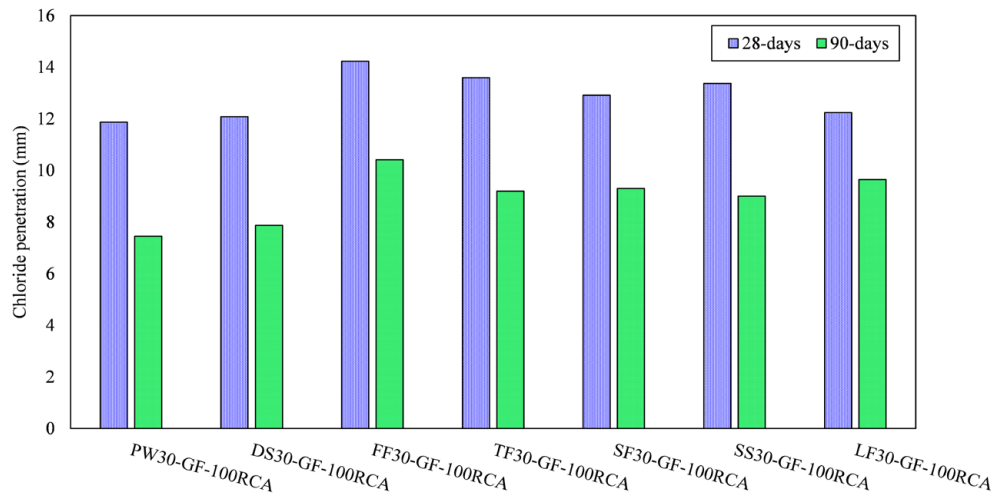


FIGURE 7. Chloride penetration in FGRAC mixes at 28 and 90-days.

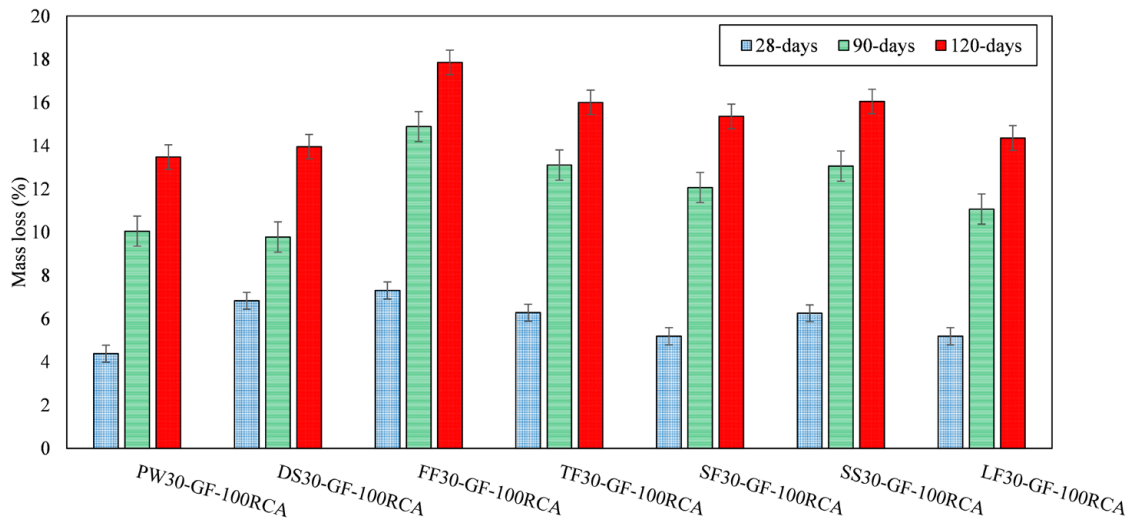


FIGURE 8. Reduction in the mass of FGRAC mixes due to the attack of sulfuric acid at various days.

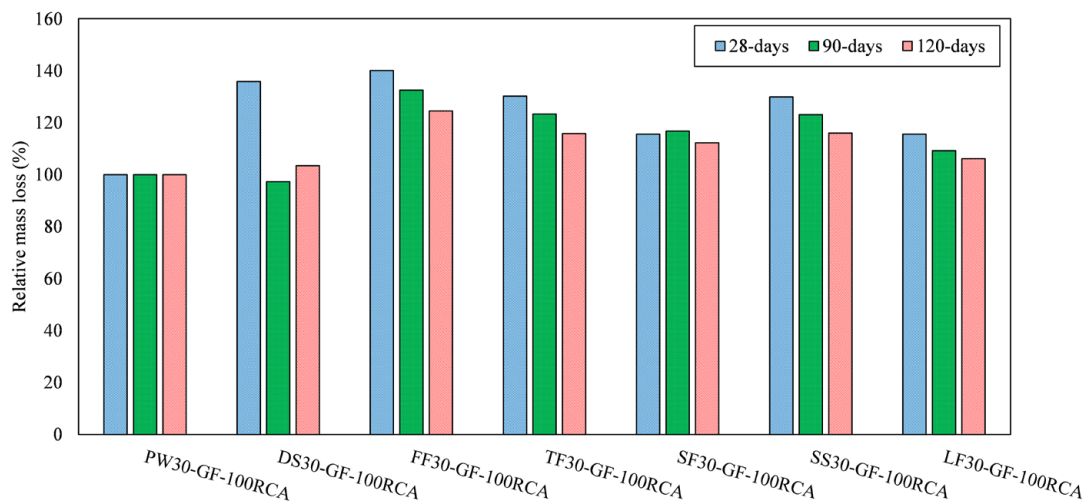


FIGURE 9. Relative mass loss of FGRAC mixes at 28, 90, and 120-days.

TABLE 6. ANOVA results for the compressive strength of FGRAC mixes at 28-days.

Groups	Counts	Sum	Average	Variance
PW30-GF-100RCA	3	78.1500	26.0500	66.560643
DS30-GF-100RCA	3	54.1462	18.0487	67.912354
FF30-GF-100RCA	3	75.4650	25.1550	36.207506
TF30-GF-100RCA	3	103.927	34.6425	128.911553
SF30-GF-100RCA	3	82.0050	27.3350	72.507675
SS30-GF-100RCA	3	71.83125	23.94375	24.922110
LF30-GF-100RCA	3	75.5950	25.198333	0.3862583

Source of Variation	SS (Sum of squares)	DOF (Degrees of freedom)	MS (Mean squares)	F	P-value	F _{crit}
Between Groups	434.72027	6	72.4533799	1.2762036	0.3290271	2.8477259
Within Groups	794.81621	14	56.7725864			
Total	1229.5364	20				

TABLE 7. ANOVA results for the split tensile strength of FGRAC mixes at 28-days.

Groups	Counts	Sum	Average	Variance
PW30-GF-100RCA	3	8.535	2.845	1.6319437
DS30-GF-100RCA	3	7.957	2.652	1.3675687
FF30-GF-100RCA	3	8.040	2.680	0.973425
TF30-GF-100RCA	3	10.810	3.603	1.6917520
SF30-GF-100RCA	3	8.122	2.707	1.7310937
SS30-GF-100RCA	3	8.017	2.672	1.0766437
LF30-GF-100RCA	3	9.045	3.015	1.6688250

Source of Variation	SS (Sum of squares)	DOF (Degrees of freedom)	MS (Mean squares)	F	P-value	F _{crit}
Between Groups	2.12158214	6	0.3535970	0.24407037	0.95387880	2.84772599
Within Groups	20.2825041	14	1.4487502			
Total	22.4040863	20				

of FGRAC. On the other hand, for the results of the tensile test, these FGRAC mixes did not display any substantial difference between them ($P = 95.4\%$ and $F < F_{crit}$), water absorption test ($P = 18.64\%$ and $F < F_{crit}$), and sulfuric acid attack test ($P = 22.8\%$ and $F < F_{crit}$). The results of the chloride penetration of different FGRAC mixes have also shown no difference with $F < F_{crit}$ which indicates that the aspects of wastewater explored in FGRAC mixing did not influence the results of the chloride penetration.

The statistical analysis of the durability and mechanical properties of FGRAC mixes portrayed that the compressive and tensile strengths are not influenced by using different types of wastewater examined in the present work. Similarly, no significant differences in the durability properties of FGRAC mixes (water absorption, chloride penetration, and concrete mass loss due to acid attack) were observed. This statistical analysis shows that the examined types of wastewater can be employed for the mixing of con-

TABLE 8. ANOVA results for the water absorption of FGRAC mixes at 90-days.

Groups	Counts	Sum	Average	Variance
PW30-GF-100RCA	3	27.585	9.195	0.863325
DS30-GF-100RCA	3	36.277	12.092	2.143481
FF30-GF-100RCA	3	33.075	11.025	4.648275
TF30-GF-100RCA	3	28.5675	9.5225	3.911643
SF30-GF-100RCA	3	33.2775	11.092	0.343743
SS30-GF-100RCA	3	35.7675	11.922	0.168882
LF30-GF-100RCA	3	31.2775	10.425	2.892077

ANOVA						
Source of Variation	SS (Sum of squares)	DOF (Degrees of freedom)	MS (Mean squares)	F	P-value	F _{crit}
Between Groups	22.199291	6	3.69988184	1.7299067	0.18648402	2.84772599
Within Groups	29.942854	14	2.138775298			
Total	52.142145	20				

TABLE 9. ANOVA results for the chloride penetration of FGRAC mixes at 90-days.

Groups	Counts	Sum	Average	Variance
PW30-GF-100RCA	3	22.3545	7.4515	2.05862475
DS30-GF-100RCA	3	23.6145	7.8715	2.26391025
FF30-GF-100RCA	3	31.2396	10.4132	2.67804012
TF30-GF-100RCA	3	27.5709	9.1903	8.68046907
SF30-GF-100RCA	3	27.9069	9.3023	3.35724627
SS30-GF-100RCA	3	26.9871	8.9957	0.81108867
LF30-GF-100RCA	3	28.9069	9.6356	4.636279603
PW30-GF-100RCA	3	22.3545	7.4515	2.05862475

ANOVA						
Source of Variation	SS (Sum of squares)	DOF (Degrees of freedom)	MS (Mean squares)	F	P-value	F _{crit}
Between Groups	18.592055	6	3.0986758	0.88585449	0.53040232	2.84772599
Within Groups	48.971317	14	3.4979512			
Total	67.563372	20				

crete without meaningfully affecting the mechanical and durability behavior of concrete.

4. CONCLUSIONS

The present study investigates the mechanical and durability behavior of recycled aggregate concrete incorporating with fly ash and glass fibers (FGRAC) manufactured using different categories of wastewater. One concrete mix was fabricated

with potable water without adding glass fibers and fly ash for the comparative analysis. A one-way ANOVA test was carried out to study the significance of using different wastewater types, fly ash, and glass fibers on the mechanical and durability behavior of FGRAC mixes. Key points of the present study are reported below.

FGRAC mix made with textile factory wastewater represented the maximum compressive strength of 37.7 MPa at 90-days that was 16.8% higher than the control mix. The addition of fly ash and glass fibers

TABLE 10. ANOVA results for the mass loss of FGRAC mixes at 90-days.

Groups	Counts	Sum	Average	Variance
PW30-GF-100RCA	3	30.1428	10.0476	3.12473535
DS30-GF-100RCA	3	29.3265	9.7755	4.90601475
FF30-GF-100RCA	3	44.6775	14.8925	10.05263175
TF30-GF-100RCA	3	39.3277	13.1092	5.591521688
SF30-GF-100RCA	3	36.1961	12.0653	7.141446047
SS30-GF-100RCA	3	39.1807	13.0602	8.130450563
LF30-GF-100RCA	3	33.1961	11.0653	6.490071047

ANOVA						
Source of Variation	SS (Sum of squares)	DOF (Degrees of freedom)	MS (Mean squares)	F	P-value	F _{crit}
Between Groups	61.0771561	6	10.179526	1.56825679	0.22813058	2.84772599
Within Groups	90.8737424	14	6.4909816			
Total	151.950898	20				

improved the compressive strength of FGRAC mixes by forming a CSH-gel and providing a bridging effect between the binder matrices. Correspondingly, the compressive strengths of FGRAC mixes made with FFW, SSW, SFW, and LFW were 7.8%, 4.8%, 7.7%, and 7% lower than the control mix.

The highest split tensile strength was portrayed by the FGRAC mix made with textile factory wastewater with a value of 4.1 MPa at 90-days that was 15.6% higher than the control mix. Correspondingly, the split tensile strengths of FGRAC mixed manufactured with FFW, SSW, SFW, and LFW were 8.3%, 3.4%, 4.9%, and 2% lower than the tensile strength of the control mix.

The FGRAC mix fabricated with domestic sewage wastewater presented the highest water absorption at 28-days that was 23.9% higher than the water absorption of the control FGRAC mix.

The chloride penetration test portrayed that all the FGRAC mixes presented higher values of chloride ion penetrations than the control mix. Fly ash reduced the chloride penetration by forming a stronger CSH bond, but the addition of glass fibers increased the voids to enhance the chloride penetration.

The attack of FGRAC mixes to 4% solution of H₂SO₄ reported that all the mixes presented higher values of mass loss as compared with the control mix. The addition of glass fibers caused an enhancement in the air voids increasing mass loss. The FGRAC mix made with fertilizer factory effluent portrayed the highest value of mass loss of concrete that was 32.5% higher than that of the control mix at 120-days.

The statistical study of the testing measurements indicated no significant difference between the various mechanical and durability performance of FGRAC mixes made with different types of effluents.

Finally, it can be concluded that all types of wastewater examined in the present study can be employed for manufacturing the concrete without significantly disturbing the mechanical and durability behavior of concrete directing towards sustainable development by overcoming the carbon footprint and low tensile strength of concrete.

AUTHOR CONTRIBUTIONS:

Conceptualization: A. Raza, B. Ali. Data curation: F.U. Haq, M. Awais, M.S. Jameel. Formal analysis: A. Raza, M. Awais Investigation: A. Raza, B. Ali, M. Awais. Methodology: A. Raza, F.U. Haq. Resources: F.U. Haq, M. Awais, M.S. Jameel. Software: A. Raza, B. Ali. Validation: B. Ali, F.U. Haq, M.S. Jameel. Visualization: M. Awais. Roles/Writing, original draft: A. Raza. Writing, review & editing: B. Ali, M. Awais, M.S. Jameel.

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