3rd International Conference on Advances in Civil and Environmental Engineering (ICACEE-2024)

University of Engineering & Technology Taxila, Pakistan

Conference dates: 21st and 22nd February 2024; ISBN: 978-969-23675-2-3

Recycled Aggregate Concrete Made with Various Types of Effluents: A Step Towards Green Concrete

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ABSTRACT

The quest for an eco-friendly environment faces challenges posed by cement's high carbon footprint, significant amounts of building and demolition waste, and industrial waste effluents. This study aims to explore the potential of recycled aggregate geopolymer concrete (RGC) produced using four types of effluents to enhance construction sustainability. Each effluent replaced fresh water entirely in RGC to assess its impact on split tensile strength (STS) and compressive strength (CS) at various curing periods. The findings indicate that the textile industry's effluent performed well in enhancing RGC's CS (25% higher than the control mix) and STS (17% higher than the control mix). Furthermore, the study showed that using effluents from textile, fertilizer, and sugar factories had no significant effect on STS but significantly influenced the CS of the concrete.

KEYWORDS: recycled aggregate concrete; geopolymer concrete; BOD; sustainability; compressive strength

1. INTRODUCTION

Urbanization, population growth, and market conditions in industrialized nations impact the production of recycled aggregate concrete (RAC) from construction waste. Proper utilization of this waste is crucial for environmental sustainability, as RAC reduces carbon footprint, minimizes transportation routes for aggregates, and manages building and demolition debris [1]. Although RAC has drawbacks like high water absorption (WA), low split-tensile strength (STS), and high porosity compared to natural aggregate concrete (NAC), it offers improved ductility, a desirable feature [2]. To reduce the carbon footprint of concrete, researchers have developed "geopolymer concrete" (GPC) using recycled coarse aggregates (RCA) and alkaline activators such as blast furnace slag, fly ash, silica fumes, and red mud, as a substitute for Portland cement [2].

Urban runoff and industrial waste contribute to environmental pollution, necessitating alternative disposal methods due to strict regulations. Concrete, the second most utilized material after wood, consumes a significant amount of freshwater, which is scarce due to rapid population growth and increased economic activity. To address this, there is a need to reduce freshwater usage, especially in the global construction industry, where concrete consumption is significant [3, 4]. By 2020, half of the world's population was projected to face water scarcity [5]. Recycling waste, particularly in concrete production, is gaining popularity as it offers cost-effective alternatives to sewage treatment [6]. Moreover, utilizing waste from concrete manufacturing can mitigate negative environmental and health impacts caused by contaminated water [6].

Studies have demonstrated the use of different types of wastewaters in concrete production. Recycled wash water in alkali-activated concrete showed no adverse effects on its development, while mortar cubes made from recycled treatment plant water exhibited similar strength to freshwater mortar cubes [7, 8]. Concrete made with treated effluent showed improved compressive strength (CS) at 28 days and using processed effluent for curing enhanced CS by 1.5%. Substituting freshwater with treated domestic sewage increased concrete strength by 9% without affecting setting time [9, 10]. Concrete made with wash water achieved 96% of the CS of freshwater concrete, while concrete tested with effluent for 180 days showed a 17% increase in CS but higher WA values [11, 12].

Based on these findings, the use of RCA and wastewater in geopolymer concrete holds promise for environmentally friendly products. Further research is needed to examine the mechanical properties (CS and STS) of recycled aggregate geopolymer concrete (RGC) blends using various types of effluents, such as sugar factory effluent (SE), fertilizer factory effluent (FE), and textile factory effluent (TE), compared to RGC blends based on freshwater.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Recycled concrete aggregates (RCA) replaced coarse aggregates in the production of geopolymer recycled aggregate concrete (GRGC). The RCA was derived from crushing concrete cylinders with a compressive strength (CS) ranging from 30 to 45 MPa at 6 to 12 months of age. Table 1 presents the properties of the recycled aggregates, which have a maximum size of 10 mm. Lawrancepur sand, with a fineness modulus of 2.25 and an apparent particle density of 2586 kg/m3, was used. Figure 1 depicts the sieve analysis of the materials used. To ensure workability, Sika ViscoCrete®-3425, a superplasticizer, was added to the GPC mix. The GRGC employed Class F fly ash (60%) and GGBS (40%) as locally available binder. A mixture of NaOH (14M molarity) and Na2SiO3 in a mass ratio of 1:2.5 served as the activator.

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	142	Minimum size	4.75 mm
Los Angeles abrasion	38.22%	Maximum size	10 mm
Bulk density	1316 kg/m^3	Specific gravity	2.23

For RGC manufacture, four different types of waste were collected from their sources. Freshwater was used to completely replace each type of wastewater. Table 2 summarizes the chemical characteristics of all effluent types used in this study.

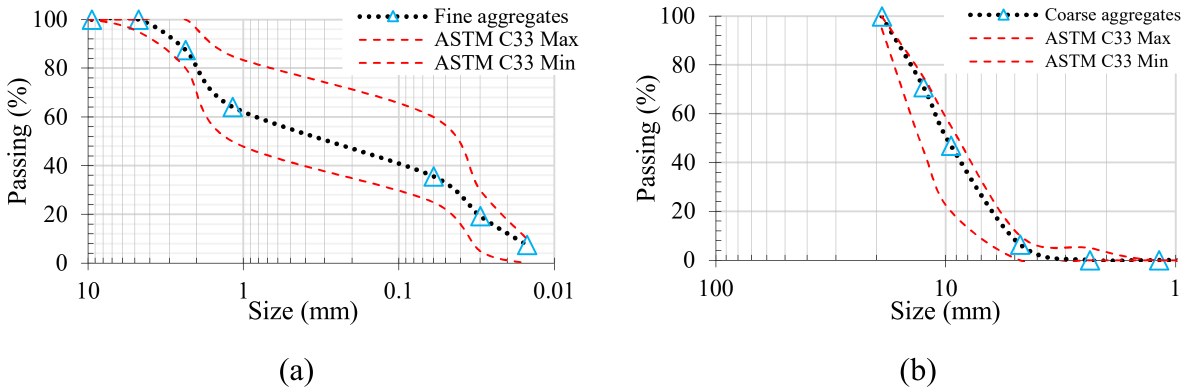

Figure 1: Granulometry (a) sand (b) RCA

Table 2: Parameters of all forms of effluent investigated in this research

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

Four recycled aggregate geopolymer concrete (RGC) mixtures were created using different types of sewage: FW, SF, FF, and TF. The performance of the RGC mix with freshwater (FW) was compared to that of mixes containing various effluents. Equal amounts of effluent were used in each RGC mix. To assess the compressive and split-tensile strength (STS) of these specimens at different curing ages, 18 cylindrical samples (150 mm x 300 mm) were produced for each RGC blend. Table 3 details the mix design of geopolymer concrete and the water absorption (WA) of recycled concrete aggregates (RCA).

A mixer with a 0.15 m3 volumetric capacity and a speed of 20 rotations per minute was used to blend the concrete for ten minutes. The aggregates were initially mixed with half of the water, followed by the remaining water and cement, and agitated for 5 minutes to achieve a uniform RGC blend. A workability test, conducted according to ASTM C143 [16], indicated a range of 85 to 110 mm for all types of wastewater. The RGC blends were cured using regular water and assessed for compressive and split-tensile strength (STS) at different ages. Compressive strength (CS) was measured at seven, twenty-eight, and ninety days, while STS was evaluated using ASTM C496 at the same curing durations [17, 18].

Table 3: Mix design of GRGC (kg/m³)

Material	Quantity	Material	Quantity
Recycled aggregate	1105	Sand	495
Water	125	Superplasticizer	40
Fly ash	245	NaOH solution (14M)	40
GGBS	170	Na_2SiO_3	110

3. DISCUSSION OF RESULTS

3.1. Compressive Strength

According to ASTM C39 [17], the compressive strength (CS) of all four RGC blends was tested at seven, twenty-eight, and ninety days. Figure 2 illustrates the CS of each RGC mix. Three specimens of each RGC blend were tested at each age, and the average results were recorded. The TF RGC blend exhibited the highest CS, while the FF RGC blend showed the lowest CS across all curing periods. The reference mix (FW) was included for comparison with other RGC blends made with different effluents. The FW mix showed a 21% increase in CS, reaching 19.5 MPa after twenty-eight days of curing. After seven days, the CS was 130% of the expected value, and after ninety days, it reached 23.7 MPa, up from the initial 13.89 MPa. Consequently, the CS of the FW mix improved with increasing curing time.

The CS of the TF blend significantly surpassed that of the FW blend at all ages. After seven days, the TF blend exhibited a CS of 17.2 MPa, surpassing the FW blend. At twenty-eight days, the TF blend's CS increased by 133% to 25.8 MPa, representing a 25% improvement over the FW blend on average. The FF blend achieved a higher strength of 21.6 MPa after ninety days of testing, but it was only 16% stronger on average than the FW blend. When TF was used in RGC mixes, higher CS was observed compared to FW. This is attributed to the reaction of fluoride and bicarbonates in TF with Al2O3 in cement and FA, forming a calcium fluoroaluminate structure that contributes to increased CS. The rapid setting and hydration of cement due to this high reactivity further enhance CS [19]. Additionally, FA's pozzolanic activity with CH and its role in densifying the cementitious mixture by filling voids and transforming the binder blend into CSH-gel contribute to improved CS.

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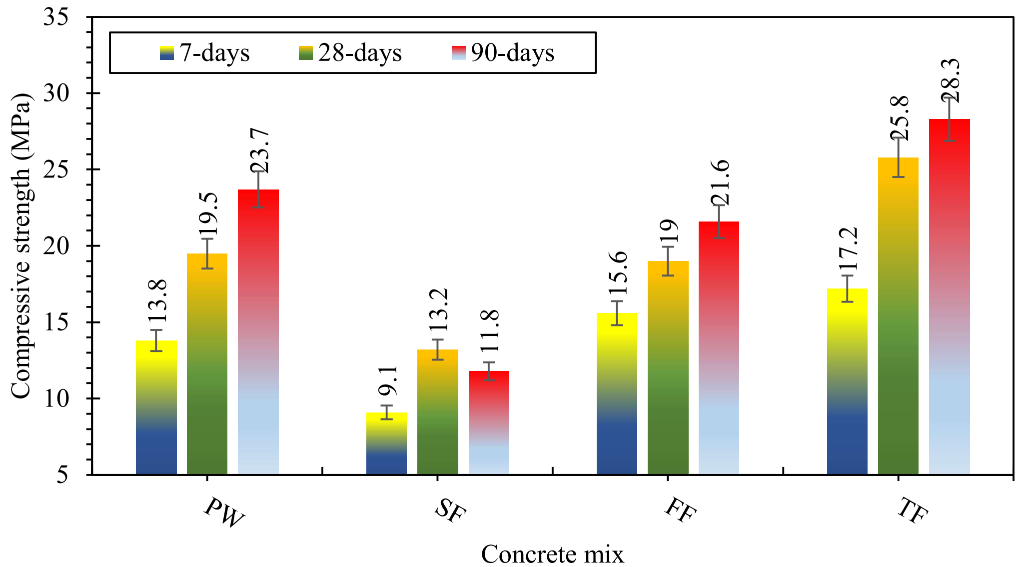

Figure 2: CS of various RGC mixes

3.2. Split Tensile Strength

Figure 3 presents the split-tensile strength (STS) of various RGC blends made with different effluent types at 7, 28, and 90 days, following ASTM C496 [18]. The mean STS of the FW blend was 2.3 MPa at 7 days, 2.6 MPa at 28 days, and 3.1 MPa at 90 days, representing 117% of its strength at 28 days after 90 days. The TF blend exhibited the highest STS, while the FF blend showed the lowest. The STS of the TF blend was 2.6 MPa at 7 days, 3 MPa at 28 days, and 3.7 MPa at 90 days, representing an 11%, 14%, and 16% increase over the FW blends at those ages. This higher STS in the TF blend is attributed to its lower bicarbonate content compared to other effluents, as higher bicarbonate levels are associated with reduced concrete STS [20]. Fly ash contributed to increased STS in RGC blends by altering the pore size distribution in the cementitious mixture and filling spaces between cement matrices, resulting in a stronger bond between RGC particles.

3.3. Relationships between CS and STS

Several studies have been published in the literature to predict the CS and STS of plain and fiber-reinforced concrete. The majority of the scholars provided the following general correlation between the CS and STS of concrete:

$$f_{sts} = k f_c'^{n} \tag{1}$$

According to Ali and Qureshi [21] the below expression can be used to estimate the STS (f_{sts}) of natural aggregate concrete (NAC) and RAC manufactured with sugar cane molasses:

$$f_{sts} = 0.106 f_c'^{0.95} \tag{2}$$

$$f_{sts} = 0.153 f_c'^{0.87} \tag{3}$$

In terms of the concrete testing age, Zain et al. [22] established a basic correlation between the CS and STS of concrete, which can be represented by Eq (4).

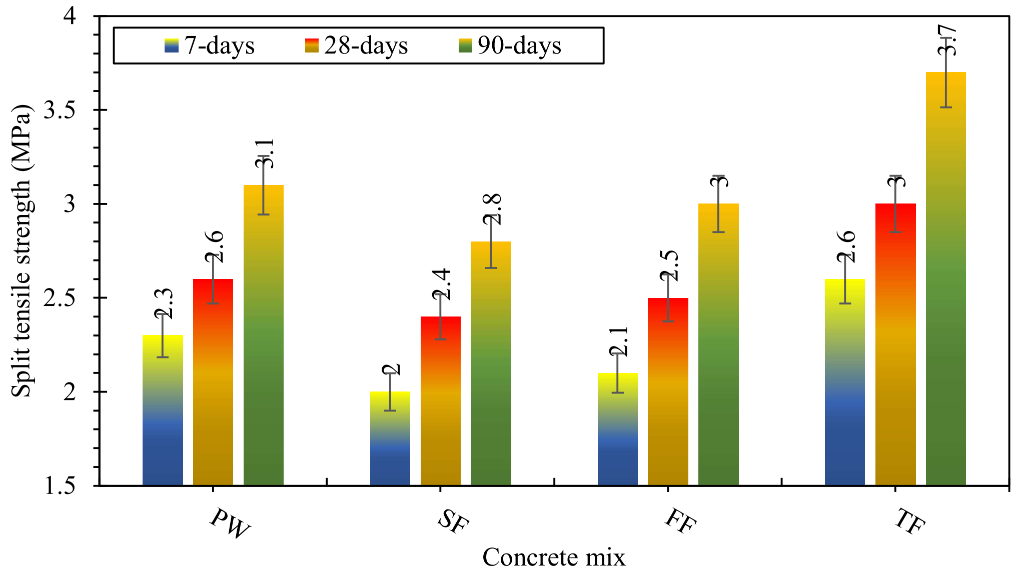

Figure 3: STS of various RGC mixes

$$f_{sts} = 0.59 \times \sqrt{f'_{c,t}} \left(\frac{t}{t_{28}}\right)^{0.04} \quad (4)$$

where $f'_{c,t}$ is concrete's ultimate CS at any testing age 't'. As per Ali and Qureshi [23], empirical study models for analyzing the STS of glass fibre reinforced recycled aggregate concrete are stated as follows:

$$f_{sts} = (-0.17 \times GF^2 + 0.23 \times GF + 0.45)\sqrt{f'_c} \quad (5)$$

$$f_{sts} = 0.332 {f'_c}^{0.63} \quad (6)$$

GF stands for the volumetric quantity of glass fibres in RAC. Dashti and Nematzadeh [24] proposed the below expressions to accurately predict the STS of concrete manufactured with standard Portland cement, Forta-Ferro fiber, and calcium aluminate cement.

$$f_{sts} = 0.363 {f'_c}^{0.50}, R^2 = 0.87 \quad (7)$$

$$f_{sts} = 0.465 {f'_c}^{0.50}, R^2 = 0.96 \quad (8)$$

In the manufacture of RAC, Wang et al. [25] employed both fine and coarse recycled aggregates and proposed a correlation between the CS and STS of RAC as described by Eq (9).

$$f_{sts} = 0.49 {f'_c}^{0.32} - 1.93 \quad (9)$$

Moreover, Wang et al. [25] suggested an expression between the f_{sts} of RAC (f_{sts}^{RAC}) and f_{sts} natural coarse aggregate concrete (f_{sts}^{NAC}) in terms of different variables of NAC and natural coarse aggregate concrete.

$$f_{sts}^{RAC} = 0.89 \frac{\left[V_{NA}^{NAC} - 0.57\left(r_{CRA} V_{CA}^{RAC} C_{RM} + r_{FRA} V_{FA}^{RAC}\right)\right]^{0.72}}{V_{NA}^{NAC}} f_{sts}^{NAC} \quad (10)$$

where V_{NA}^{NAC} is the volumetric fraction of natural aggregates, r_{CRA} is the substitution ratio of RCA, V_{CA}^{RAC} is the volumetric fraction of coarse aggregates, V_{FA}^{RAC} represents the volumetric fractions of fine aggregates, C_{RM} is the content of RCA residual mortar, and r_{FRA} is the replacement ratio of fine aggregates.

Figure 4 illustrates the empirical correlation between compressive strength (CS) and split-tensile strength (STS) for various RGC blends. The figure also includes theoretical predictions showing the relationship between the compressive and tensile strength of RGC blends made with different effluents. These test results were compared to several proposed models (shown in Table 4) that describe the correlation between the compressive and tensile strength of plain concrete blends after twenty-eight days of curing. Figure 5 compares the experimental data of STS for RGC blends with the predictions of different models.

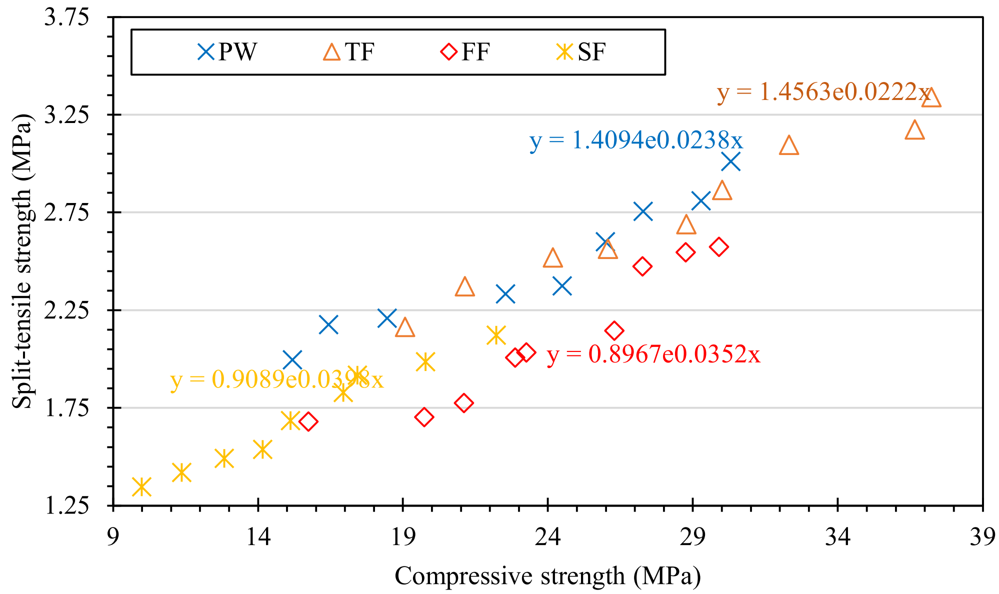

Figure 4: Forecasts for the CS and STS of RGC blends using various codes

According to ACI 318 [26], the percentage disparities for FW, TF, FF, and SF mixes were 11.25%, 7.94%, 30.85%, and 27.91%, respectively, which were the largest discrepancies compared to other models. This could be due to ACI 318 [26] being designed for ordinary concrete with freshwater and natural coarse aggregates (NCA), while this study used recycled coarse aggregates (RCA) for RGC mixes. The percentage disparities for FW, TF, FF, and SF blends, as per Xiao et al. [27], were 21.65%, 22.25%, 7.96%, and 15.89%, respectively. GB: 10,010 [28] showed disparities of 14.65%, 14%, 0.19%, and 12.47% for FW, TF, FF, and SF blends, respectively. Iravani [31] indicated disparities of 15.65%, 0.15%, 8.76%, and 15% for SF, FF, TF, and FW blends, respectively. Zain et al. [30] estimated disparities of 12.5%, 3.4%, 10.95%, and 11.89% for SF, FF, TF, and FW blends, respectively. Eurocode 2–04 [29] showed disparities of 10%, 21.33%, 2.77%, and 3.3% for

SF, FF, TF, and FW blends, respectively. JCI-08 [32] indicated disparities of 19.64%, 17.82%, 5.75%, and 21.27% for FW, TF, FF, and SF blends, respectively. Finally, NZS: 3101:2006 [33] revealed disparities of 11%, 13.66%, 4.68%, and 2.33% for FW, TF, FF, and SF blends, respectively. Based on the equations provided in this study, Eurocode 2–04 [29] is recommended for predicting the STS of FW and TF blends, JCI-08 [32] for estimating the STS of FF blend, and NZS: 3101:2006 [33] for forecasting the STS of SF mix, as they showed the highest accuracies.

Table 4: Correlation between CS and STS of normal concrete existing in past research

Standard/Research	Formula (MPa)
ACI 318 [26]	$f_{sts} = 0.55 \times \sqrt{f_c'}$
Xiao et al. [27]	$f_{sts} = 0.24 \times {f_c'}^{0.65}$
GB: 50010 [28]	$f_{sts} = 0.19 \times {f_c'}^{0.75}$
Eurocode 2–04 [29]	$f_{sts} = 0.30 \times {f_c'}^{2/3}$
Zain et al. [30]	$f_{sts} = \frac{0.8f_c'}{0.1\times(0.8f_c')+7.11}$
Iravani [31]	$f_{sts} = 0.301 \times (0.8f_c')^{0.65}$
JCI-08 [32]	$f_{sts} = 0.13 \times {f_c'}^{0.85}$
NZS: 3101 [33]	$f_{sts} = 0.44 \times \sqrt{f_c'}$

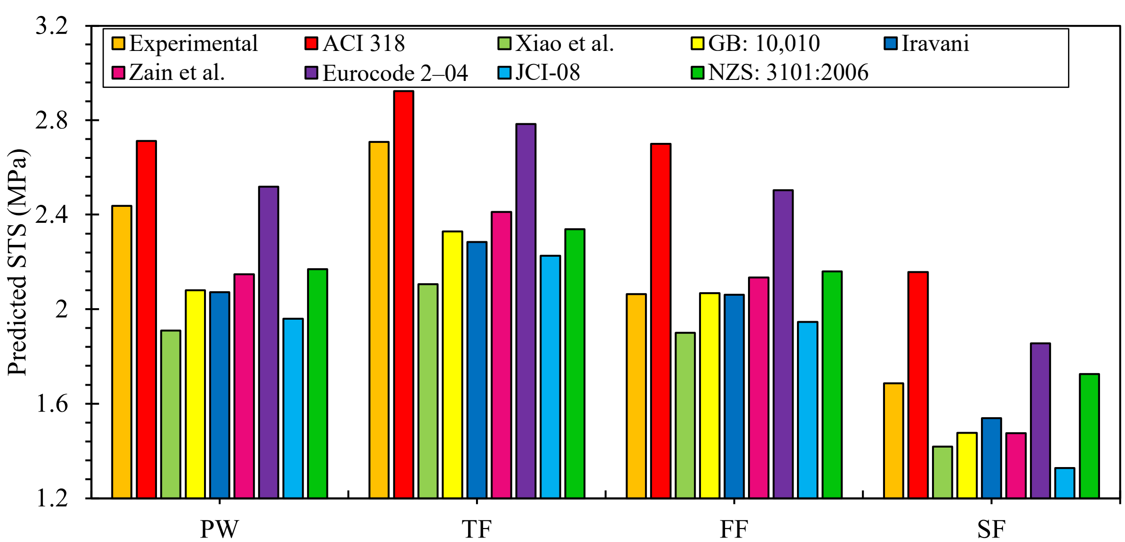

Figure 5: Comparison of STS forecasts for RGC blends using various equations

4. CONCLUSIONS

The following important conclusions can be drawn from the experimental findings:

1. The compressive strength (CS) of the RGC blend using textile manufacturing effluent was 25% higher on average than that of freshwater concrete. However, when sugar plant effluent was used, the CS decreased by half due to the presence of organic materials that tend to absorb water. RGC blends with fertilizer plant effluent showed the highest CS increase of 91%, while those with sugar plant effluent had a 90% higher strength than freshwater RGC. The formation of CSH gel in RGC contributed to the improved CS.
2. In split-tensile strength (STS) tests, concrete made with textile industry effluent exhibited a 17% higher STS compared to freshwater concrete. RGC blends with fertilizer plant effluent displayed the highest STS at 97% compared to freshwater, while those with sugar industry effluent and SE had STS increases of 92% and 95%, respectively, compared to freshwater blends.

ACKNOWLEDGMENTS

None.

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