MECHANICAL PROPERTIES OF ELECTRIC ARC FURNACE SLAG INCORPORATED RECYCLED AGGREGATE CONCRETE

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ABSTRACT

Partially substituting recycled aggregate (RA) with Electric Arc Furnace Slag (EAFS) in the production of concrete may provide an efficient approach to lower natural aggregate consumption while also providing an alternative method of disposal for EAFS. It may also be an approach to improve the mechanical and durability properties of RA concrete as it lacks mechanical and durabilty properties compared to natural aggregate concrete. In this work, EAFS was collected from local steel manufacturers which was used to replace 0%, 25%, 50%, and 75% of RA concrete samples. Concrete with three target compressive strengths, i.e., 17.23, 20.68, and 24.13 MPa, were prepared. Concrete samples' mechanical parameters, such as compressive and tensile strength, flexural strength, modulus of elasticity, and Poisson's ratiowere measured in accordance with applicable ASTM standards. A review of test results reveals that by replacing 50% of RA with EAFS, compressive and tensile strength can be improved. Flexural strength and modulus of elasticity, on the other hand, were observed to increase with increasing replacement of RA by EAFS. Overall, a 50% replacement ratio for RA with EAFS may result in concrete with optimum mechanical qualities.

Keywords: *EAF Slag, Recycled Stone Aggregate, Compressive Strength, Modulus of Elasticity*

1. INTRODUCTION

Bangladesh is one of the fastest developing countries in the world. Development and improvement of infrastructure in Bangladesh depends heavily on production of concrete. To meet the coarse aggregate demand, natural stone aggregate has to be imported from various countries.In this regard demolished concrete recycled as aggregate for new concrete production may be an economic alternative source. However, concrete produced from RA are found to be inferior with respect to mechanical and durability properties with respect to natural stone aggregate (NA) (Ahmad et al., 2020). Hence, RA may be replaced partially by Electric Arc Furnace Slag (EAFS) which is a waste by product in steel industries (Pellegrino et al.,2013; Sekaran et al.,2015;Monosi et al., 2016). In Bangladesh most of the steel industries use induction furnace to produce steel from which induction furnace slag is generated. Many researchers have shown that partial use of induction furnace slag as replacement of brick and recycled coarse aggregate enhances the mechanical and durability properties of concrete (Ahmad and Rahman,2018; Roy et al.,2023; Rahman and Ahmad, 2022).Only a limited number of researches in the existing literature have investigated the use of EAFS slag produced in Bangladesh as substitute for NA or RA in concrete. These studies have found that the utilization of EAFS slag leads to an increase in both compressive and tensile strengths (Gulshan et al., 2017; Rahman and Ahmad, 2020). Hence, a somewhat detailed study was conducted in this work that examined different aspects of mechanical properties of EAFS replaced RA concrete. For this, concrete with target compressive strength of 17.23 MPa, 20.68 MPa, and 24.13 MPa wereprepared by substituting EAFS for RA at varying percentages of 0%, 25%,50% and 75% for each strength level. The study examined the impact of adding EAFS on various mechanical properties of both fresh and hardened concrete. These variables included slump value, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and Poisson's ratio.Review of these test results, recommendations with approximate formula were given as aguideline for effective use of these two waste products.

2. METHODOLOGY

The entire experimental procedure comprises many steps, including material collection, property determination, sample preparation using ACI mix design, specimen curing, testing after 28 days of curing, and ultimately comparing the results to establish a suitable conclusion and recommendation.

2.1 Cement

The concrete samples were prepared using Type – 1 Portland Cement (BDS EN 197-1:2003, CEM I, 52.5N, ASTM C-150). The BUET concrete laboratory recently identified some essential features of this cement.

Table 1: Properties of cement

Properties	Materials	Test Standard
Specific Gravity	3.15	ASTM C128
Normal Consistency (%)	25.5	ASTM C 187
Initial SettingTime (Minutes)	158	ASTM C 191
Initial SettingTime (Minutes)	367	ASTM C 191
28 days Compressive Strength (MPa)	45.94	ASTM C 109

2.2 Fine Aggregate

The experimental endeavour utilized fresh, natural coarse sand, specifically Sylhet sand, as the fine aggregate. The fineness modulus (FM), absorption capacity, and specific gravity of the sand were determined according to the applicable standards.

Table 2: Properties of fine aggregate

Properties	Materials	Test Standard
Specific Gravity	2.6	ASTM C128
Water Absorption (%)	1.62	ASTM C127
Fineness Modulus	3.02	ASTM C136
Unit Weight(kg/m3)	1568.41	ASTM C 29

2.3 Recycled Stone Aggregate (RSA)

Collected concrete blocks were obtained from the structural components of the demolished buildings. The concrete samples were pulverized using a mechanical crusher apparatus. The recycled stone aggregate was fragmented and then sorted using conventional sieves ranging from 25 mm to 4.75 mm. The gradation curve was carefully adjusted to conform to the specified limits defined by ASTM C33. The measured properties of recycled stone aggregate, including apparent specific gravity, bulk specific gravity (in both saturated surface dry (SSD) and oven-dry (OD) conditions), water absorption capacity, fineness modulus (FM), loose condition unit weight, dense condition unit weight, and LA abrasion value, are listed in Table 3.

Table 3: Material properties of coarse aggregate

Properties	Materials		Test Standard
	RSA	EAFS	
Apparent Specific Gravity	2.68	3.19	ASTM C127
Bulk Specific Gravity (SSD)	2.48	3.11	ASTM C127
Bulk Specific Gravity (OD)	2.36	3.07	ASTM C127
Absorption Capacity (%)	4.98	1.32	ASTM C127
Fineness Modulus	7.516	7.227	ASTM C136
Loose Unit Weight (kg/m3)	1252.71	1679.69	ASTM C 29
Dense Unit Weight (kg/m3)	1376.21	1845.54	ASTM C 29
Loss Angles Abrasion (%)	40.08	17.12	ASTM C131

2.4 Electric Arc Furnace Slag (EAFS)

The EAFS was obtained from the Abul Khair Steel (AKS) company, which specializes in producing reinforcing bars, located in Chattogram, a port city in southern Bangladesh. The slag aggregates were subjected to laboratory sieving utilizing standard sieve sizes ranging from 25mm to 4.75mm. The particle size distribution and gradation curve of the Electric Arc Furnace Slag (EAFS) complied with the specifications outlined in the ASTM C33 standard. Before conducting the mix design, many characteristics of the slag aggregate were assessed and listed in Table 3. These included the apparent specific gravity, bulk specific gravity in both saturated surface-dry (SSD) and oven-dry (OD) conditions, water absorption capacity, fineness modulus (FM), unit weight in loose and dense conditions, and LA abrasion value.

Examining the leaching capability of EAFS is crucial for their environmentally friendly use in concrete as a substitute for aggregates, given the presence of heavy metal oxides in EAFS. To aid the study, a Toxicity Characteristics Leaching Potential (TCLP) test was performed following the guidelines of USEPA 1311 (USEPA 1993). The TCLP test result, as presented in Table 4, unambiguously validates the potential use of EAFS as aggregates in concrete. This is because all the metal concentrations leached from EAFS were significantly lower than the regulatory standard set by USEPA 1311.

Table 4: Leaching of heavy metals from EAFS]

Metal	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Leaching(mg/L)	-0.012	-0.031	0.004	-0.9	0	0.027	-0.002
USEPA Limit	1.000	5.000	-	0.200	-	5.000	-

2.5 Mix Design and Mixing Method

Three concrete mixtures were created following the ACI 211.1-91 technique, each with target strengths of 17.23, 20.68, and 24.13 MPa. In these mixtures, the recycled stone aggregate (RSA) was replaced by Electric Arc Furnace Slag (EAFS) at 0%, 25%, 50%, and 75%. Table 5 presents the precise values of the detail mix design for each situation. Before adding the coarse aggregate and fine aggregate into the concrete mix, both were thoroughly wet on the surface. The slump values for each concrete mix design with twelve different strengths were obtained using ASTM C138 and are presented in Table 5. For each goal strength and replacement ratio, 15 samples with dimensions of 200mm by 100mm were manufactured. These samples were then subjected to compressive strength, splitting tensile strength, and modulus of elasticity testing using the guidelines outlined in ASTM C39, ASTM C496, and ASTM C469. Furthermore, three small prism samples measuring 100*100*300mm were fabricated for each level of strength to assess flexural strength following the guidelines outlined in ASTM C78. There was no sign of EAFS segregation during the process of mixing concrete.

Table 5: Concrete mix design (Quantity for 1m^3 of concrete)

Target Strength (MPa)	Slag Ratio	W/C	Water (kg/m3)	Cement (kg/m3)	RSA (kg/m3)	EAFS (kg/m3)	Sand (kg/m3)	Measured Slump(mm)
17.23	0.00	0.75	192.76	257.01	899.08	0.00	812.26	39
	0.25		192.76	257.01	674.31	301.42	795.91	37
	0.50		192.76	257.01	449.54	602.84	779.57	34
	0.75		192.76	257.01	224.77	904.26	763.23	47
20.68	0.00	0.68	192.76	283.47	899.08	0.00	790.42	38
	0.25		192.76	283.47	674.31	301.42	774.08	33
	0.50		192.76	283.47	449.54	602.84	757.73	36
	0.75		192.76	283.47	224.77	904.26	763.23	44
24.13	0.00	0.63	192.76	305.96	899.08	0.00	771.85	40
	0.25		192.76	305.96	674.31	301.42	755.51	37
	0.50		192.76	305.96	449.54	602.84	739.16	32
	0.75		192.76	305.96	224.77	904.26	722.82	27

3. ILLUSTRATIONS

3.1 Compressive Strength of Concrete

The compressive strength of concrete was determined after 28 days of curing using a compression test conducted on cylindrical specimens in the laboratory, following the guidelines of ASTM C39. Figure 1 displays the graphical representation of the compressive strength data for three target strengths (17.23, 20.68, and 24.13 MPa) for varied EAFS replacement ratios (0%, 25%, 50%, and 75%).

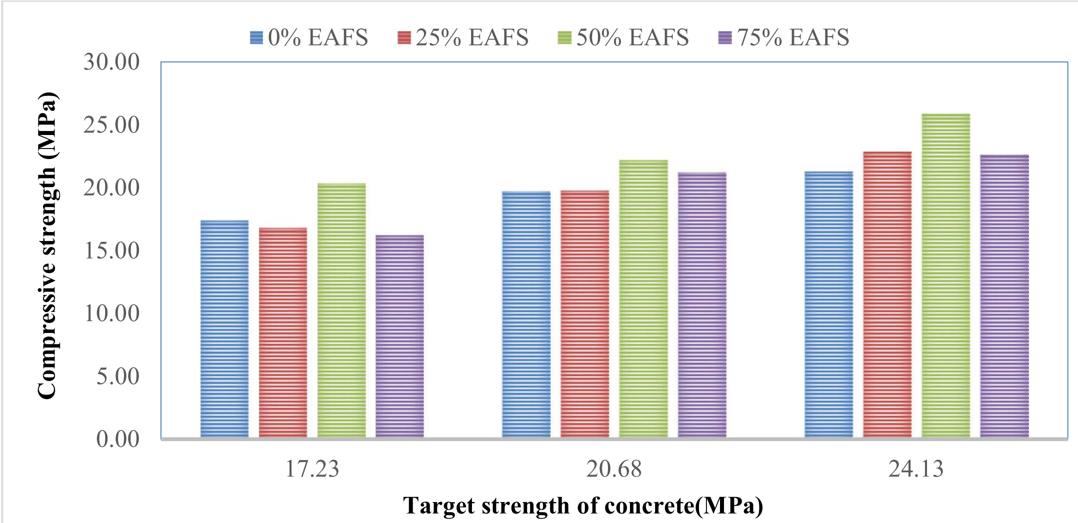

Figure 1: Compressive strength of concrete for different target strengths and EAFS ratio

After a curing period of 28 days, the compressive strength increased by 12.68 to 21.47% when 50% EAFS was employed as a substitute, compared to when 0% EAFS was used.The presence of a strong interfacial transition zone (ITZ) around the electric arc furnace slag (EAFS) may be responsible for the increased bond strength and positive impact on the mechanical characteristics of slag aggregate concrete (Arribas et al., 2015). However, when 75% of the EAFS (Electric Arc Furnace Slag) is substituted, all three target strengths exhibit a decrease in compressive strength.

3.2 Splitting Tensile Strength of Concrete

The splitting tensile strength of cylindrical specimens was evaluated after 28 days of curing by ASTM C496. The study's findings are visually depicted in Figure 2. The experimental results indicate that a 50% replacement ratio of EAFS yields superior results compared to other replacement ratios. The increased bond strength may be attributed to a strong interfacial transition zone (ITZ) between EAFS and RSA. Once again, the increase in the case of 50% replacement was determined to be approximately 14.93-15.69%.

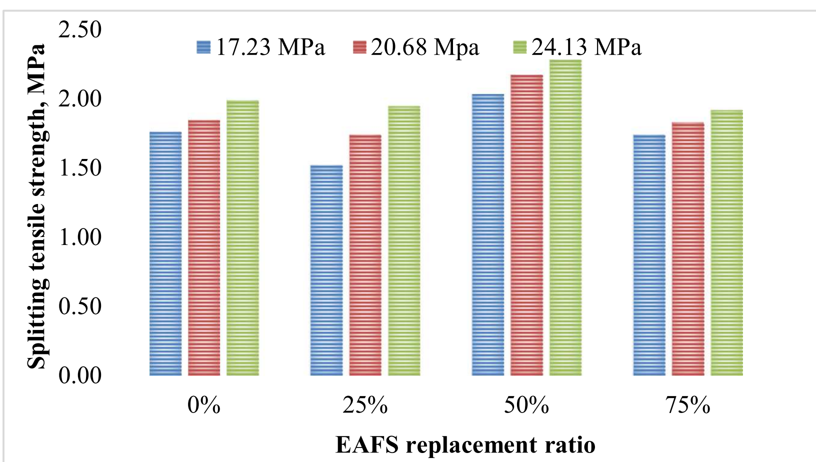

Figure 2: Splitting tensile strength of concrete for different EAFS ratio

3.2.1 Relationship between Tensile Strength and Compressive Strength

Figure 3-5 illustrates the relationship between the splitting tensile strength and the square root of compressive strength for varied ratios of EAFS replacement, corresponding to each target strength.

The experimental analysis observed a linear correlation, and the ACI code established the relationship. The graphs indicated that the measured value of splitting tensile strength was lower than the values suggested by ACI 318-14 for concrete with normal density. According to ACI 318-14, the recommended formula for calculating splitting tensile strength is $f_t=0.556\sqrt{f'_c}$ in MPa.

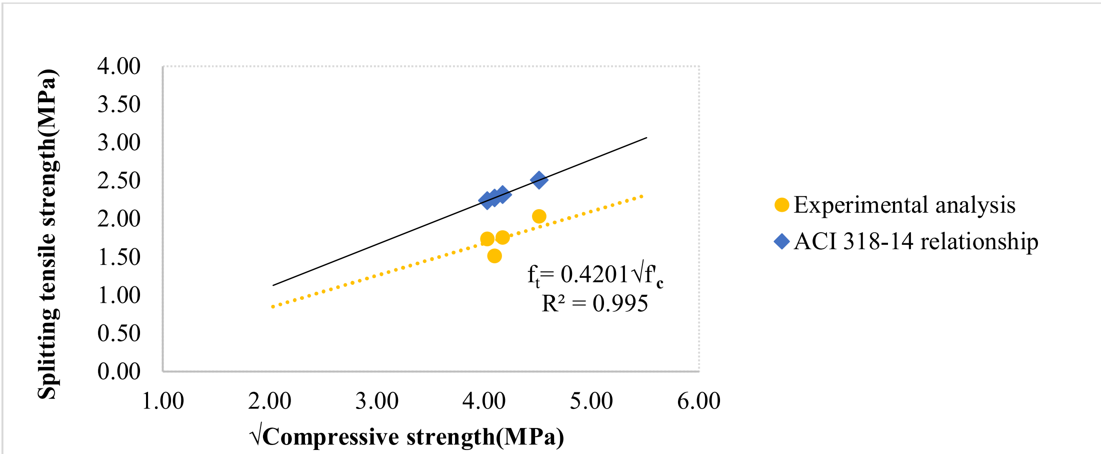

Figure 3: Relationship between tensile strength and compressive strength for different EAFS ratio(17.23MPa)

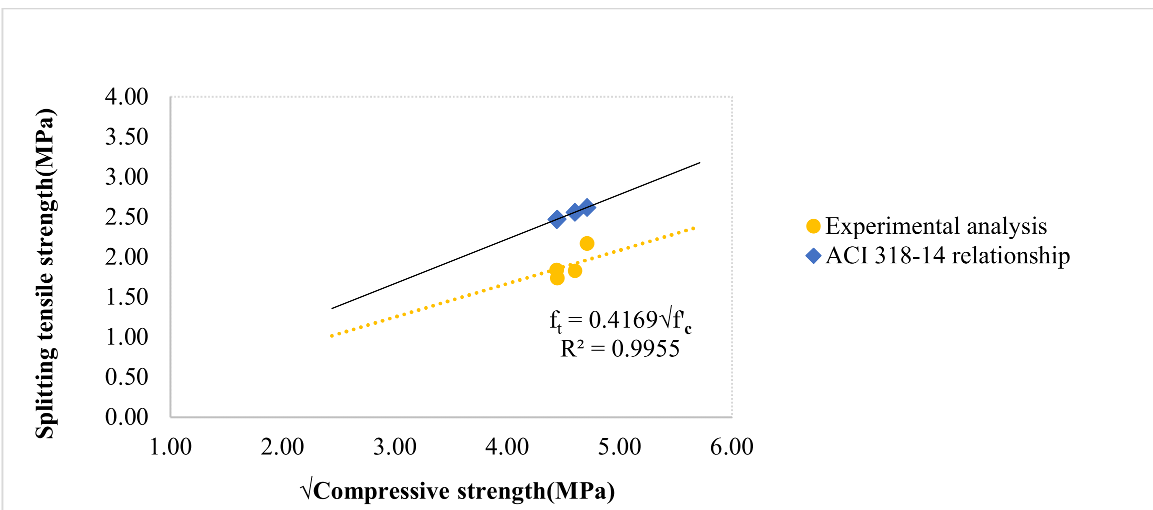

Figure 4: Relationship between tensile strength and compressive strength for different EAFS ratio(20.68 MPa)

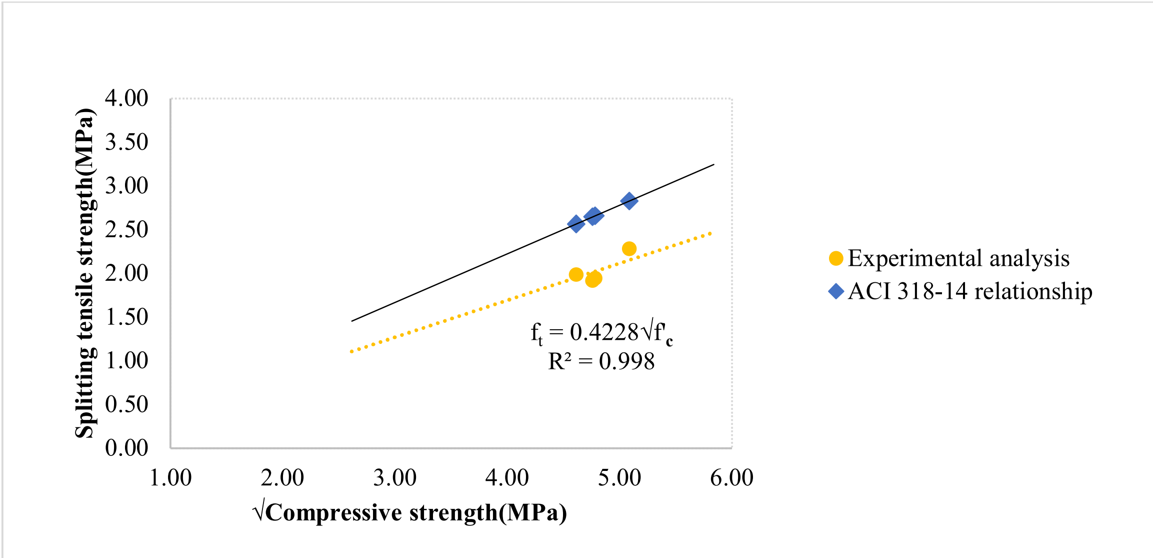

Figure 5: Relationship between tensile strength and compressive strength for different EAFS ratio(24.13MPa)

3.3 Flexural Strength of Concrete

The flexural strength test of prism specimens was performed by ASTM C78. The prism specimens were placed in the Universal Testing Machine (UTM) and subjected to third-point loading, as seen in Figure 6. The sample was aligned to the support by gradually applying a loading rate of 100 and 150 N/sec, according to the expected load. It was then subjected to a continuous and uniform loading until failure, without sudden impact. The maximum load was recorded for each specimen. The majority of the failure was concentrated in the central section. The graph in Figure 7 displays the flexural strength values derived for various EAFS ratios.

Figure 6: Test setup to determine flexural strength of concrete and failure surface of recycled aggregate that contains EAFS.

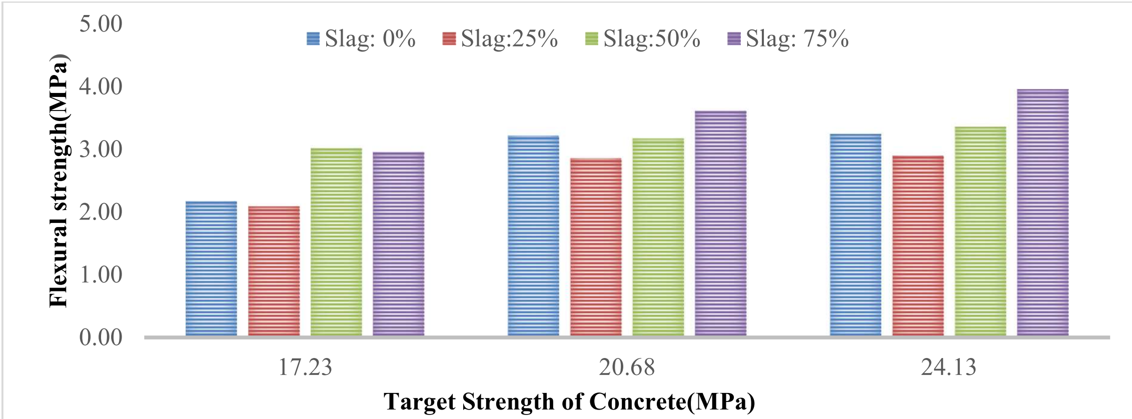

Figure 7: Flexural strength of concrete for different EAFS ratio

3.3.1 Relationship between Flexural Strength and Compressive Strength

Figure 8-10 illustrates the relationship between flexural strength and the square root of compressive strength for varied ratios of EAFS replacement, corresponding to each target strength. A linear correlation was observed in both the experimental analysis and the relationship defined by the ACI code. The graphs indicated that the measured flexural strength was lower than the values recommended by ACI 318-14 for normal density concrete, which is $f_r=0.62\sqrt{f'_c}$in MPa.

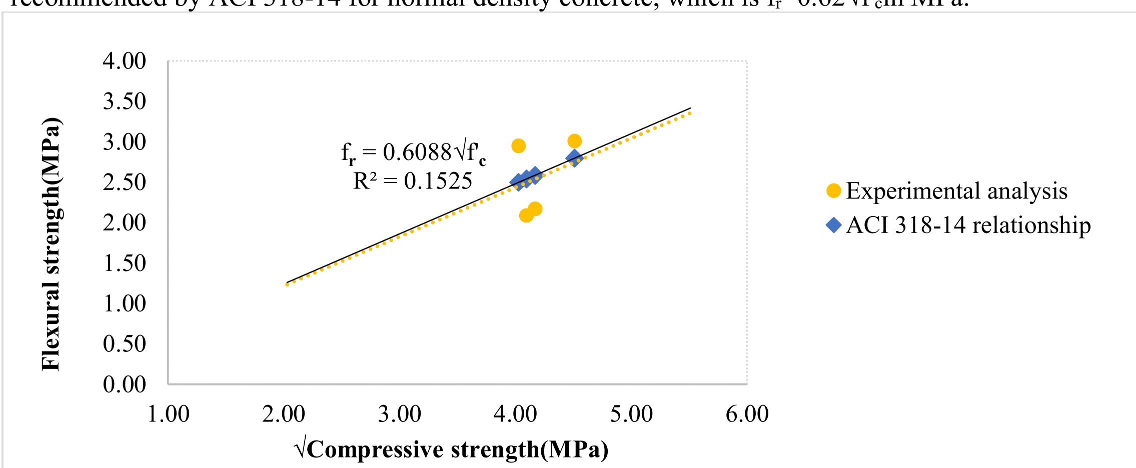

Figure 8: Relationship between flexural strength and compressive strength fordifferent EAFS ratio(17.23MPa)

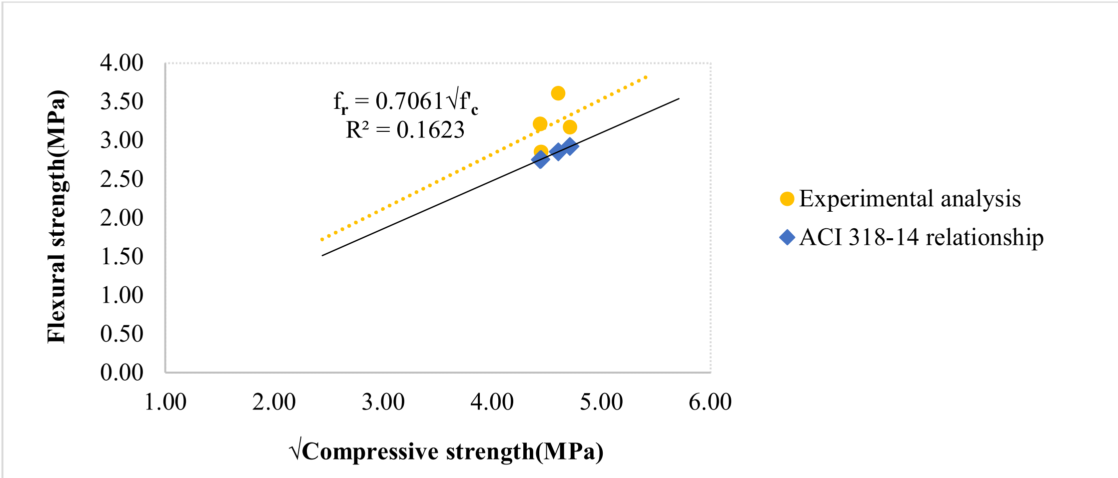

Figure 9: Relationship between flexural strength and compressive strength for different EAFS ratio(20.68MPa)

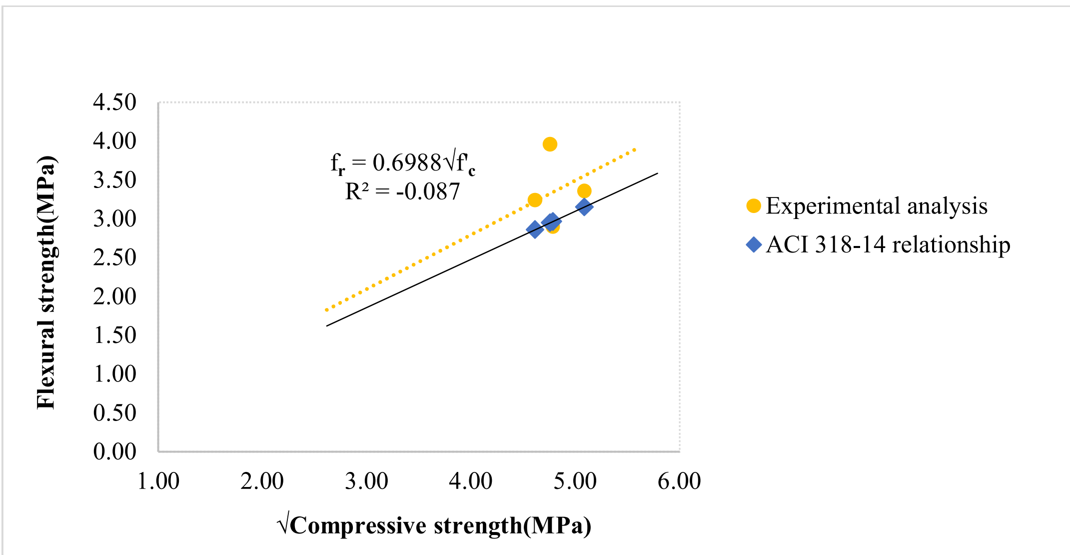

Figure 10: Relationship between flexural strength and compressive strengthfor different EAFS ratio(24.13MPa)

3.4 Modulus of Elasticity and Poisson's ratio of Concrete

The Young's modulus of elasticity (MoE) of concrete was determined using the ASTM C469 standard test method after 28 days. The test was conducted for various replacement ratios in three different design strengths. The results were presented in Figure 5. The modulus of elasticity was observed to rise as the amount of RSA with EAFS increased.The increment in modulus of elasticity from 0% slag to 75% slag replacement was determined in the range of 23.30% to 54.21%.The rise in strength was accompanied by a fall in Poisson's ratio, as indicated in Table 6.

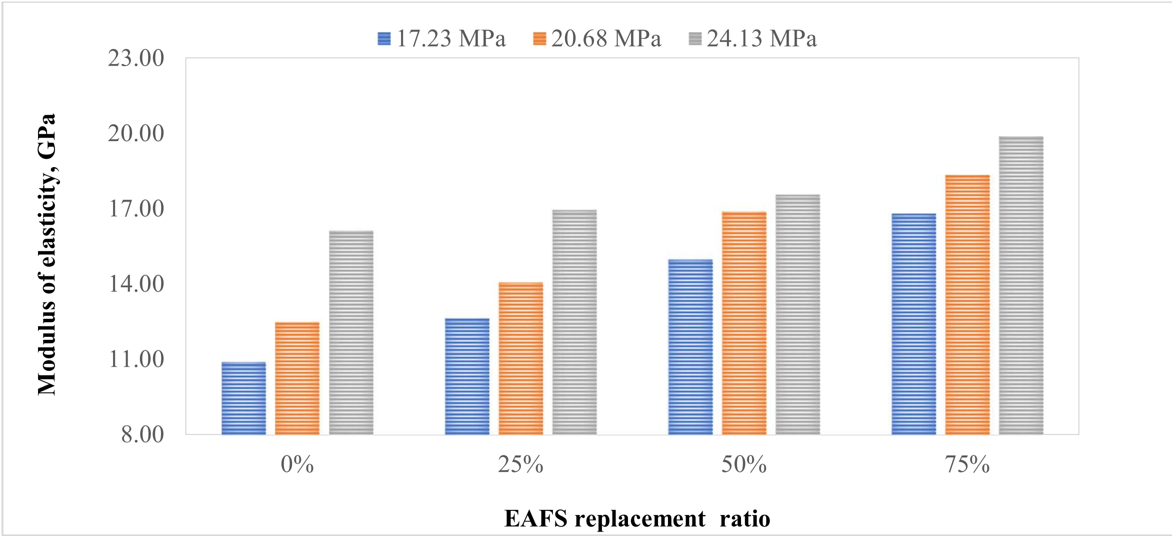

Figure 11: Modulus of elasticity of concrete for different EAFS ratio

3.4.1 Relationship between Modulus of Elasticity and Compressive Strength

3.4.2 The ACI 318-14 code (ACI 2014) suggested the following relationship between the concrete compressive strength (f'_c) and the modulus of elasticity (E_c) of natural stone aggregate concrete,where $E_c=4.7\sqrt{f'_c}$ in GPa.

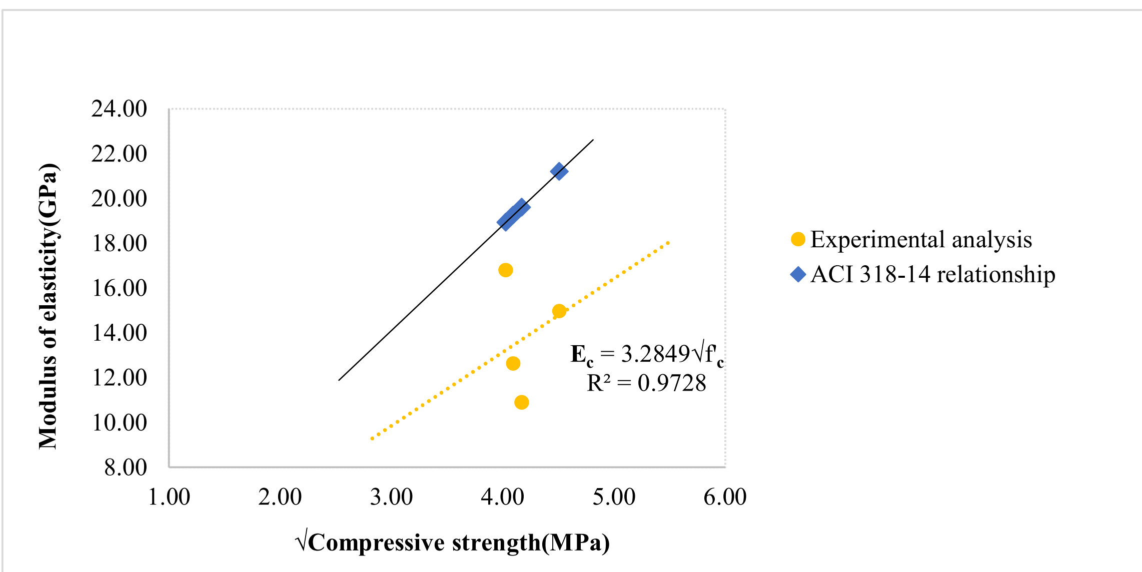

Figure 12: Relationship between modulus of elasticity and compressive strength for different EAFS ratio(17.23MPa)

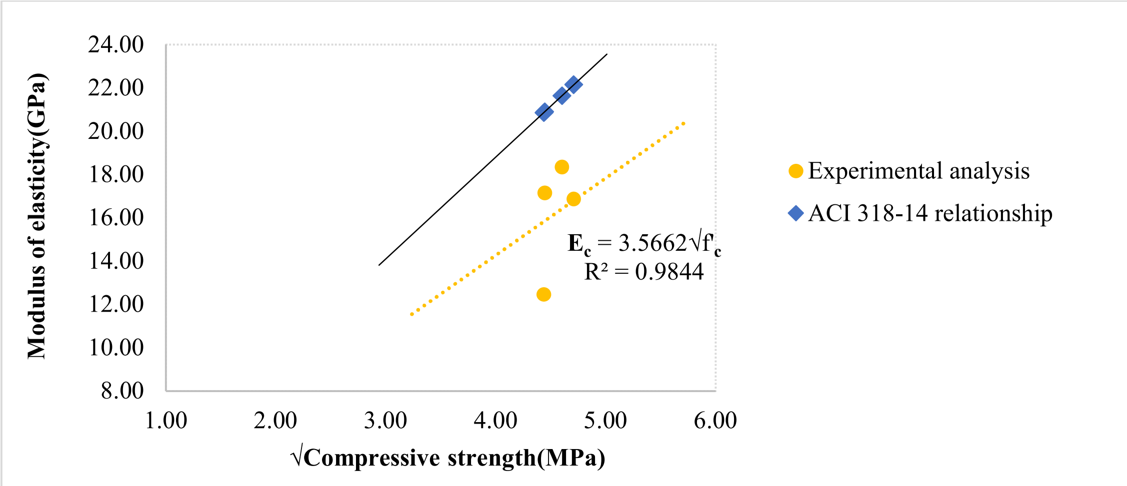

Figure 13: Relationship between modulus of elasticity and compressive strength for different EAFS ratio(20.68MPa)

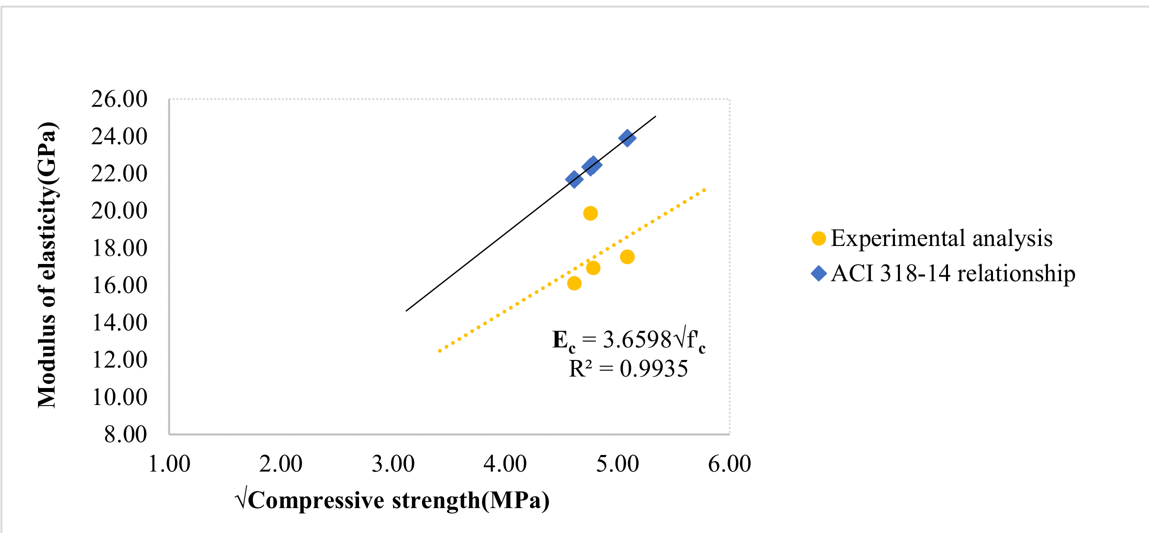

Figure 14: Relationship between modulus of elasticity and compressive strength for different EAFS ratio(24.13MPa)

Figure 12–14 illustrates the linear relationship between the modulus of elasticity and the square root of compressive strength for varied ratios of EAFS replacement for each target strength. The following relationships for the recycled stone aggregate (RSA) and the electric arc furnace slag (EAFS) were also developed. For RSA-EAFS aggregate concrete (17.23 MPa), $E_c = 3.2849\sqrt{f'_c}$; for 20.68 MPa concrete, $E_c = 3.5662\sqrt{f'_c}$; and for 24.13 MPa concrete, $E_c = 3.6598\sqrt{f'_c}$ in GPa. This equation may help to find the modulus of elasticity of concrete for any percent replacement of EAFS.Using the RSA and EAFS as coarse aggregate, there was a slight reduction in modulus of elasticity with respect to the natural aggregate in concrete. A higher modulus of elasticity was found in a high percentage of slag with a low water-to-cement ratio.

Table 6: Poisson's ratioof slag aggregate concrete

Strength	17.23MPa	20.68MPa	24.13MPa
0% EAFS	0.23	0.17	0.15

25% EAFS	0.25	0.22	0.19
50% EAFS	0.22	0.18	0.16
75% EAFS	0.21	0.17	0.15

4. CONCLUSIONS

The conclusion derived from this experimental study on evaluating the mechanical qualities of concrete made with recycled stone aggregate blended with electric arc furnace slag can be summarized as follows:

• The substitution of 50% EAFS resulted in the highest improvement in compressive strength, surpassing the desired design strength. Once again, the increase was determined to be approximately 12.68-21.47% for a 50% replacement.

• The splitting tensile strength rose as the 50% replacement ratio of the Electric Arc Furnace Slag (EAFS) increased. The increase in the case of 50% replacement was around 14.93-15.69%. The relationship between splitting tensile strength and compressive strength has been proposed as follows: for 17.23MPa concrete, $f_t=0.4201\sqrt{f'_c}$; for 20.68MPa concrete, $f_t=0.4169\sqrt{f'_c}$; and 24.13MPa concrete, $f_t=0.4228\sqrt{f'_c}$.

• The study revealed that the flexural strength exhibited a positive correlation with the replacement ratio, indicating that as the percentage of replacement materials increased, the flexural strength also increased. The test results for flexural strength showed that replacing 50% of the recycled stone aggregate with EAFS resulted in a strength improvement ranging from 3.61% to 38.71%. The proposed correlation between flexural strength and compressive strength corresponds to the outlined below: for 17.23MPa concrete, $f_r=0.6088\sqrt{f'_c}$; for 20.68MPa concrete, $f_r=0.7061\sqrt{f'_c}$; and 24.13MPa concrete, $f_r=0.6988\sqrt{f'_c}$.

•The modulus of elasticity was shown to rise as the replacement ratio increased. Replacing 50% of the EAFS, the modulus of elasticity increased by 8.87%to 37.34 % compared to concrete made with 100% RA.

From these findings it may be recommended to substitute 50% of RA with EAFS in concrete production. This will significantly improve mechanical strength measures while ensuring that all values remain within permissible bounds. EAFS and RA are waste products that can be effectively utilized by as coarse aggregate in concrete.

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