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Performance of the Mechanical Properties of Concrete Modified with Coarse Glass Aggregate and Incorporation of Polypropylene Fibers

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ABSTRACT

Millions of tons of glass are wasted annually. Recycling glass is an important professional function for resource conservation, waste reduction, and environmental impact mitigation. Incorporating polypropylene fibers into concrete has been proven effective in enhancing its compressive, tensile, and flexural resistance while addressing concerns related to brittleness. The main goal of this study is to find out what happens to the mechanical properties of concrete samples when Coarse Glass Aggregate (CGA) is used as a partial replacement for a natural aggregate of the same size, along with polypropylene fibers. The experimental approach involved preparing concrete mixes with incremental glass ratios, ranging up to 50% with 10% increments. Mechanical tests were performed on the specimens. The results revealed an increase in compressive and tensile strength with increasing glass ratios, peaking at an optimum of 40%. Beyond that, the strength declined. Furthermore, the optimal glass ratio exhibited a remarkable improvement of 31.92% in compressive strength and 41.24% in tensile strength compared to samples devoid of glass content. Also, the flexural test conducted with a 40% glass ratio yielded an optimal mixture displaying a strength 44.78% greater than the control experiment. The proposed equations to correlate compressive strength versus splitting tensile strength and splitting tensile strength versus flexural strength are consistent with the existing research. However, the correlation between compressive strength and flexural strength is consistently underestimated. In conclusion, this study demonstrates that the utilization of glass waste in concrete production has the potential to serve as a sustainable solution for waste management while simultaneously improving the mechanical properties of concrete.

Keywords: Coarse aggregate, Compressive strength, Flexural strength, Polypropylene fiber, Tensile strength, Waste glass.

1 INTRODUCTION

The utilization of glass items has experienced significant growth, resulting in substantial quantities of glass waste. Glass is manufactured in various types, comprising packaging or container glass, plate glass, bulb glass, and glass tubes (Rashad, 2014). However, the process of manufacturing glass contributes to a significant environmental impact through the release of atmospheric emissions during melting operations, primarily carbon dioxide (CO2). The annual worldwide production of glass reaches approximately 130 million metric tons, with a substantial portion of it being wasted, as only 21% of the produced glass is recycled (Tiseo, 2020). Consequently, proper waste management of glass has become an important environmental concern, driven by the urgent need to conserve landfill capacity, protect natural resources, and reduce the construction sector's carbon footprint (Mohajerani et al., 2017).

Recycled glass offers a viable alternative to conventional aggregates, such as sand or gravel, as a substitute for a portion of the binder used in composition of concrete. The widespread application of recycled crushed glass as an environmentally conscious substitute for both coarse and fine aggregates in concrete has been extensively observed (Amin et al., 2023, Özkılıç et al., 2023, Ahmed and Rana, 2023). There are several articles that have explored the incorporation of waste glass as a partial alternative for concrete aggregates. Abd et al. (2019) investigated three different gradations with different percentages for replacing coarse, fine, and combined aggregates. In their study, a concrete mixture was created with a weight-based ratio of (1:2:4) for (cement: sand: coarse aggregate), accompanied by a water-to-cement (w/c) ratio of 0.4 to achieve the desired 30-35 MPa compressive strength. Evaluation involved 13 cubic specimens (100x100x100 mm) undergoing tests for compressive strength and water absorption after 7 or 14 days of curing. Furthermore, 13 prism specimens (20x20x70 mm) underwent flexural strength testing under corresponding curing periods. The outcome reveals that the highest compressive and flexural strengths are achieved when 30% of sand and coarse aggregate are replaced with waste glass, surpassing both the control sample and other replacement percentages. This increase in waste glass content leads to a chemical interaction among the cement's alkaline components and the active silica-based minerals in some aggregates. Additionally, the study concludes that waste glass with a particle diameter smaller than 0.075 mm exhibits higher strength compared to larger particle sizes. Keryou and Ibrahim (2014) studied the utilize of CGA obtained from windows glass as a partial replacement for coarse aggregates in conventional concrete. This extensive research involved examining 54 well-cured concrete specimens in total, comprising 18 cubes, each measuring 150 mm, which were employed for compression analysis, 18 cylinders sized at 100x200 mm, were utilized to assess splitting tension, and 18 prisms with dimensions of 100x100x400 mm were tested to determine flexural properties. The mixture ratios based on weight were precisely (1: 1.96: 2.73: 0.5) for (cement: sand: gravel: w/c) used. Various replacement percentages of 0, 20, 25, and 30% by weight were examined. The findings revealed a progressive rise in strengths as the percentage of CGA increased, up until a certain threshold was reached, beyond which the strength started to decline. The optimal replacement percentage of 25% resulted in the highest impact, with significant increases of 30% in compressive strength, 38% in tensile strength, and 31% in flexural strength observed after 28 days of age. Olofinnade et al. (2016) explored the prospective utilization of waste glass as a partial replacement for natural sand and gravel in concrete. The preparation of the mixture involved weight-based procedures, utilizing a ratio of 1:2:4 (cement: sand: gravel) and a w/c ratio of 0.5. A total of 90 concrete cubes were produced for evaluating compressive strength, with tests conducted at intervals of 3, 7, 14, 28, 42, and 90 days. Each cube measured 150x150x150 mm. Similarly, cylindrical specimens, with a diameter of 100 mm and a height of 200 mm, were employed to assess splitting tensile strength using the same age and quantity mix proportion. The experiment investigated the effects of varying the percentage of crushed glass from 0% to 100% in 25% increments by weight while maintaining a constant w/c proportion. They revealed that the split tensile and compressive strengths reduced as the proportion of recycled glass improved compared to the reference blend. in contrast, the 25% waste glass concrete mix performed remarkably well and showed promise for generating lightweight concrete. Otunyo and Tornwini (2016) conducted a study where a total of 54 concrete cubes were produced. They utilized CGA as a partial replacement for coarse aggregate in conventional concrete, employing different dosages (0%, 5%, 10%, 15%, 20%, and 25%). They revealed that a discernible reduction in compressive strength occurred with increasing proportions of CGA over different time intervals (7, 14, and 28 days). Satisfactory compressive strength was obtained at a glass replacement ratio of 5% and 10%. Moreover, glass powder has been extensively researched as a favorable binder for concrete and provides numerous advantages. When incorporated into concrete, glass powder undergoes a chemical reaction with calcium hydroxide ($Ca(OH)_2$), resulting in the creation of additional compounds that enhance the material's strength (Paul et al., 2018, Mejdi et al., 2019).

Several researchers have investigated the incorporation of fibers into concrete, driven by the overarching objective of enhancing its mechanical properties. Alhozaimy et al. (1996), they conducted tests using a w/c of 0.45 to assess compressive strength through cylindrical specimens measuring 152 x 305 mm, as well as to evaluate flexural strength using prismatic specimens with dimensions of 102 x 102 x 356 mm. Also discerned the impact of employing polypropylene (PP) fibers at reduced volumetric ratios (up to 0.3%) on the salient characteristics of the concrete matrix. The findings revealed that the inclusion of PP fibers did not have a statistically momentous influence on the compressive or flexural strength of the concrete. Nevertheless, the inclusion of these fibers resulted in an enhancement of the concrete's flexural toughness and impact resistance. Moreover, Mohod (2015) delved into the consequences of incorporating varying quantities of PP fibers into high-strength concrete, focusing on the mechanical properties, across diverse curing conditions. The study determined the optimal content of PP fibers by varying the proportion from 0% to 2%. Compressive, split tensile, and flexural strength increased with increasing in fiber dosage up to 0.5%, after which it started decreasing. Therefore, the optimum proportion of fiber found was 0.5%. RAS (2006) showed that concrete with the addition of PP fiber serves a crucial function in increasing ductility and slightly increasing compressive strength. The experiments involved measuring the compressive strength of five sets of concrete cubes, each with dimensions of 100x100x100 mm (resulting in a total of 45 cubes), at 7, 28, and 56 days. Additionally, the splitting strength of concrete cylinders, measuring 100 mm in diameter and 200 mm in height, was assessed. This encompasses a total of 15 cylinders, all subject to a consistent w/c ratio of 0.45 across all mixes. It was deduced that the optimal fiber ratio amounted to 0.5%; beyond that value, the mechanical properties decreased. Jayaram et al. (2022) studied the influence of fiber on various mechanical properties of M25-grade concrete. A total of 30 cube samples were utilized to assess compressive strength, accompanied by 20 cylindrical samples for evaluating splitting tensile strength, and an additional 10 beam specimens for the analysis of flexural strength. The research emphasized examining the effects of incorporating different ratios of PP fibers (0.5%, 1%, 1.5%, and 2%). Notably, 1% addition of fibers was incorporated into the concrete. exhibited significant improvements in compressive, flexural, and split tensile strength, with enhancements of 29.8%, 4.92%, and 3.21%, respectively. Furthermore, it was observed that PP fibers effectively served as a crack stopper in hardened concrete. Alsadey and Salem (2016) conducted an investigative study to ascertain the precise quantity of PP fibers essential for achieving the utmost compressive strength in M25 grade concrete. According to the results, the inclusion of PP fibers led to a significant improvement in compressive strength. Particularly, with a fiber content of 2%, there was compressive strength a remarkable 12% increased. Latifi et al. (2022) conducted a study where they determined that the inclusion of fibers had no discernible impact on the compressive strength of the mixes. However, notable improvements were observed in both tensile and flexural strengths. Additionally, the blends exhibited improved flexural toughness and ductility. The observed phenomenon can be attributed to the fiber's capacity to effectively span cracks in the concrete, consequently impeding its propagation.

In addition, other researchers have used PP fiber with recycled waste. Das et al. (2018) they investigated the impacts of incorporating PP fibers into natural aggregate concrete and recycled aggregate concrete. They examined various percentages of fiber inclusion, including 0.5%, 0.75%, and 1%. The findings indicated that the addition of fibers had a minimal impact on the compressive strength of the concrete. However, significant improvements were observed in the tensile and flexural strengths of both natural and recycled concrete aggregate. Notably, the results highlighted an optimal fiber content of 0.5% that yielded the best outcomes for both experimental series. Orouji et al. (2021) cast 24 distinct batches of compression specimens, each measuring 150×150×150 mm, designated for aging at intervals of 7, 28, and 90 days. Similarly, they prepared 12 separate mixtures for beam specimens, measured at 500×150×150 mm, intended for comprehensive flexural testing. They evaluated concrete incorporating different percentages of glass powder and PP fiber matrices. The results indicated that an optimal glass content of 25% led to increased compressive and flexural strengths of the concrete. Furthermore, the simultaneous utilization of 25% glass powder and 1.5% fibers yielded the highest flexural and compressive strengths in the concrete. The combined utilize 25% of pulverized glass and 1.5 % fibers resulted in approximately a 1.6-fold improvement in compressive strength, a 4-fold enhancement in flexural toughness, and a 13.2-fold increase in beam ductility.

After an extensive literature review, it was observed that no research has been conducted on the utilization of recycled crushed glass as a partial substitute for coarse aggregate, along with the inclusion of polypropylene fiber. Therefore, this study aims to investigate the feasibility of modifying concrete by incorporating recycled glass as Coarse Glass Aggregate (CGA) at various ratios (0%, 10%, 20%, 30%, 40%, and 50%) as a partial substitute for coarse aggregate while maintaining the same size as natural coarse aggregate. Additionally, a constant percentage of PP fiber (0.2% of the volume fraction) will be included, which is determined as the optimum ratio based on the literature. An experimental program will be carried out to assess the mechanical properties of the altered concrete in comparison to the reference conventional concrete. Furthermore, the correlation among compressive strength, tensile strength, and flexural strength will be analyzed.

2 EXPERIMENTAL METHODOLOGY

2.1 Materials Properties

This section displayed the material properties that were used in the investigation.

2.1.1 Natural Coarse Aggregate

Locally available gravel from the Aski Kalak-Erbil quarry was used. The gravel was clean and natural, passing 100% through the opening (25mm) and retaining 100% in the opening (4.75mm), as indicated by the sieve analysis test results depicted in Fig. 1. This figure demonstrates the utilization of gravel within the lower and upper limits specified in ASTM-C33 (2013).

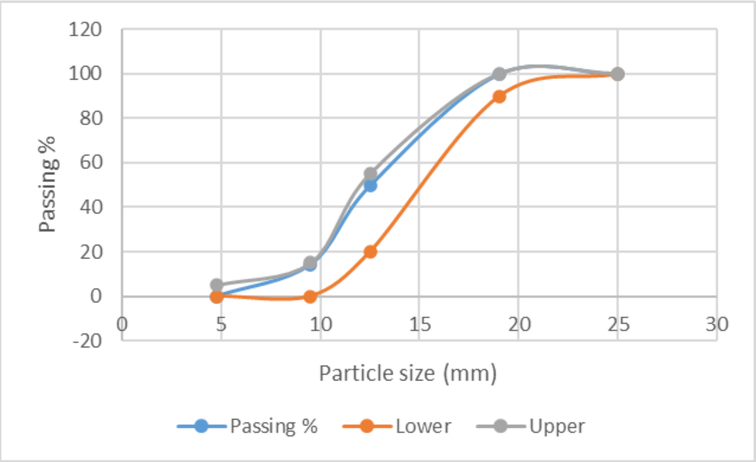

Fig. 1. Distribution of coarse aggregate using a grading curve with ASTM upper and lower limits.

2.1.2 Coarse Glass Aggregate

Once waste window glass was collected from the shop's store, it was crushed using a hammer. The resulting crushed glass was then utilized in this study to match the equivalent size of the gravel as well as the size of the control mix. Coarse Glass Aggregate (CGA) is of comparable size to gravel. The CGA shown in Fig. 2 is used in thicknesses of 4mm and 6mm. Furthermore, the sieve analysis test results shown in Fig. 3 within ASTM specification's lower and upper limit in ASTM-C33 (2013).

Fig. 2. Crushed glass utilized as a partial replacement for coarse aggregate in concrete.

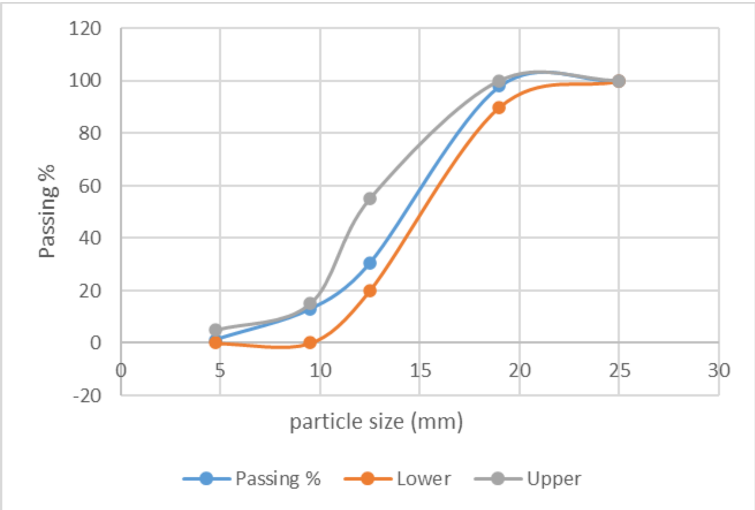

Fig. 3. Grading curve for crushed glass with ASTM limits with lower and upper.

2.1.3 Natural Fine Aggregate

Locally available sand from the Aski Kalak-Erbil quarrying source was used. The sand was clean, natural, and had a maximum particle diameter of 4.75 mm. The sieve analysis test results are presented in Fig. 4 within the lower and upper limits specified in the ASTM standard (ASTM-C33, 2013).

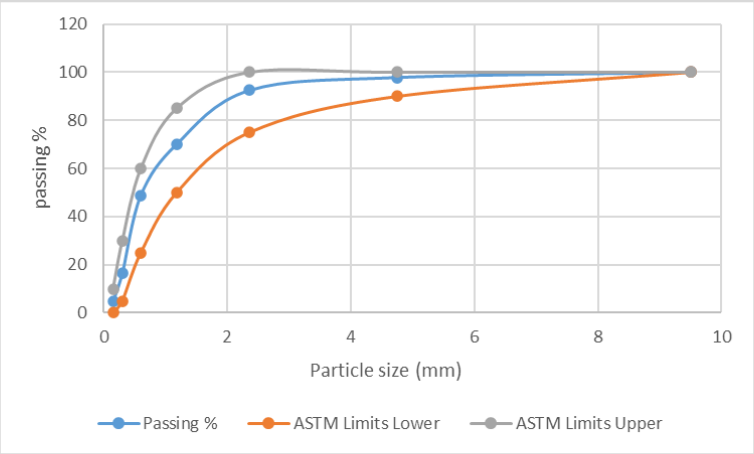

Fig. 4. Grading curve for the sand with ASTM limits.

2.1.4 Cement

Concrete mix designs have been made using regular Portland cement. The cement's physical and chemical characteristics have been examined and are shown in Table 1, conforming according to the specification of ASTM-C150 (2016)

Table 1: Cement's physical and chemical characteristics.

Test category	Type of tests	Results	ASTM-C150 (2016)
Chemical tests	SiO_2	19.2	-
	Al_2O_3	4.65	-
	Fe_2O_3	3.22	-
	CaO	63.55	-
	MgO	1.87	≤ 6
	SO_3	2.48	≤ 6
	Lime Saturation Factor	1.01	0.66 – 1.02
	Loss On Ignition (L.O.I)	3.26	≤ 6
	Insoluble residue (I.R)	0.71	≤ 0.75
	Total Alkalis	0.05	-
Physical tests	Initial setting time	180 min.	Not less than 45min.
	Final setting time	245 min.	Not more than 600min.
	Compressive strength three days age	27.6 MPa	14.7 MPa, lower limit
	Compressive strength seven days age	52.2 MPa	22.5 MPa, lower limit
	Fineness Modulus of Cement	300 m^2/kg	230 m^2/kg, the lower limit
	Specific gravity	3.15	
	Density	1400 kg/m^3	

2.1.5 Polypropylene Fiber

The length of the sample is 12mm. The density of the sample is 900 kg/m^3. A volume equivalent to 0.2% of the total volume is used in the mixes. Fig. 5 displays a sample of polypropylene.

Fig. 5. Polypropylene fiber.

2.2 Concrete mix design

The mixing procedure employed in this research study adhered to the guidelines set by (ACI-Committee-211, 1991). Subsequently, the prepared mixture was carefully poured into lubricated molds and subjected to vibration. For this investigation, a constant water-to-cement ratio of 0.5 was used, and the mix design ratio was 1:1.7:2.5 (cement: sand: gravel). The respective quantities were determined by weight, as presented in Table 2

Table 2: Mıxture desıgn wıth varıous glass content ratıos per m3

GROUP	Polypropylene fiber m^3	Cement kg	Water kg	Sand kg	Natural Gravel kg	CGA kg
G1	0.002	1400	700	2380	3500	0
G2	0.002	1400	700	2380	3150	350
G3	0.002	1400	700	2380	2800	700
G4	0.002	1400	700	2380	2450	1050
G5	0.002	1400	700	2380	2100	1400
G6	0.002	1400	700	2380	1750	1750

2.3 Casting and curing

Before adding the concrete to the mixer, the molds were thoroughly cleaned and oiled to facilitate the easy removal of the cast concrete. The concrete vibrating table is used to consolidate fresh concrete in cylinder, cube, and prism molds, in accordance with ASTM-C1170 (2002). Each layer was vibrated for approximately 30 seconds using an electric vibrator. After keeping the freshly cast concrete in the molds for 24 hours. then for 28 days, it was cured in the water tank. as shown in Fig. 6, following the guidelines of ASTM-C31/C31M-10 (2010).


Fig. 6. Water tank for cured specimen at a constant temperature.

2.4 Characteristics of the Specimens

2.4.1 Compressive Strength

The capacity of a structure or material to bear stresses on its surface without deflection or cracking is known as compressive strength. It was tested on 100x100x100 mm cubes, for each batch 3 cubes were tested, and the average of the samples was taken. In total, 18 specimens were cast for compressive strength testing according to ASTM-C39 (2014). Fig. 7 shows a compression testing machine.


Fig. 7. Specimen under compressive machine test.

2.4.2 Splitting Tensile Strength

Applying a diametric compressive load at some point along the entire length will cause failure in the splitting tensile strength test. Three samples were chosen for each mix design, utilizing 100x200 mm cylinders, and the average of these three samples was taken. A total of 18 cylinders were cast to evaluate the tensile strength of each cylinder. In accordance with ASTM-C469 (2014), thin steel sheet strips were installed at the bottom and top of the cylinders to ensure consistent loading, as shown in Fig. 8.

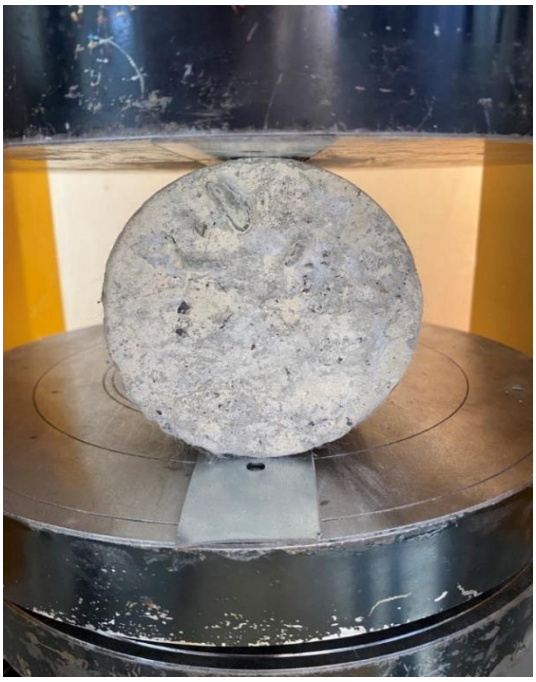

Fig. 8: Splitting tensile test for the cylinder.

2.4.3 Flexural Strength

In accordance with ASTM-C293-02 (2002), three (100x100x500) mm prisms were cast and tested under central point loading to determine the flexural strength of the concrete. Eighteen samples were selected and cast to undergo the flexural test. Each side of the beam was lined with a 50 mm margin from its edge to ensure accuracy during the test. The machine was aligned to accurately position the midpoint for the test. Fig. 9 illustrates the specimen under the flexural machine loading.

Fig. 9. Prism specimen under the flexural test.

3 RESULTS AND DISCUSSION

Experiments on compressive strength, splitting tensile strength, and flexural strength were carried out to ascertain the performance of the mechanical properties of concrete modified with CGA and the incorporation of polypropylene fibers. Table 3 displays the average outcomes for each experiment.

Table 3: Compressive, splitting tensile, and flexural strength results for various content cga.

Glass Ratio (%)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
0	33.15	2.91	2.68
10	35.04	3.26	3.03
20	37.90	3.55	3.24
30	39.04	3.80	3.54
40	43.73	4.11	3.88
50	31.21	2.94	3.00

3.1 Compressive Strength

Figure 10 shows how the compressive strength of concrete with fixed amounts (0.2% by volume) of polypropylene changes with different amounts of CGA, from 0% to 50%. The first mix, which was all-natural gravel and had a strength of 33.15 MPa, was used as a control. When 10% of the natural gravel was replaced with CGA in the second mix, the strength went up to 35.04 MPa, which was 5.70% more than the strength of the control. Also, the third mix (20% CGA) increased to 37.90 MPa (+14.33%). Likewise, mix four (30% CGA) continues to increase the compressive strength, which is 39.04 MPa (+17.77%). The final positive effect of the CGA replacement was recorded in mix five (40% CGA), reaching the maximum value in the trend, which is 43.73 MPa (+31.92%). After that, the compressive strength of mix six (50% CGA) went down to 31.21 MPa (-5.85%), which was less than the strength of the control mix. However, the observed phenomenon

(Keryou and Ibrahim, 2014) can be attributed to the fact that the CGA possesses a more angular shape, in contrast to the naturally rounded coarse aggregates. As a result, the CGA provides enhanced interlocking and greater frictional forces within the concrete mixture. Furthermore, it is important to note that beyond a 40% replacement ratio, a decline in compressive strength was noticed. This decrease can be attributed to the smooth surface and flakiness of the CGA particles when compared to the natural coarse aggregates.

The optimum ratio is 40% CGA to those results. However, Park et al. (2004) concluded that the best ratio of glass to compressive strength is also 30%. They announced that this is because the surface of the waste aggregate and the cement paste stick together less well, and the compacting factor goes down when coarse aggregate is replaced. Nevertheless, in the current study, after adding too much CGA (i.e., more than 40%), the compressive strength would decrease since CGA has a smoother surface than natural gravel and no rough corners so the chemical bond between the cement mortar and aggregate becomes weak. So, in this study, the best amount of CGA was found to be 40%. In the current experiment, the ratio of PP fiber was fixed to 0.2% for all mixes.

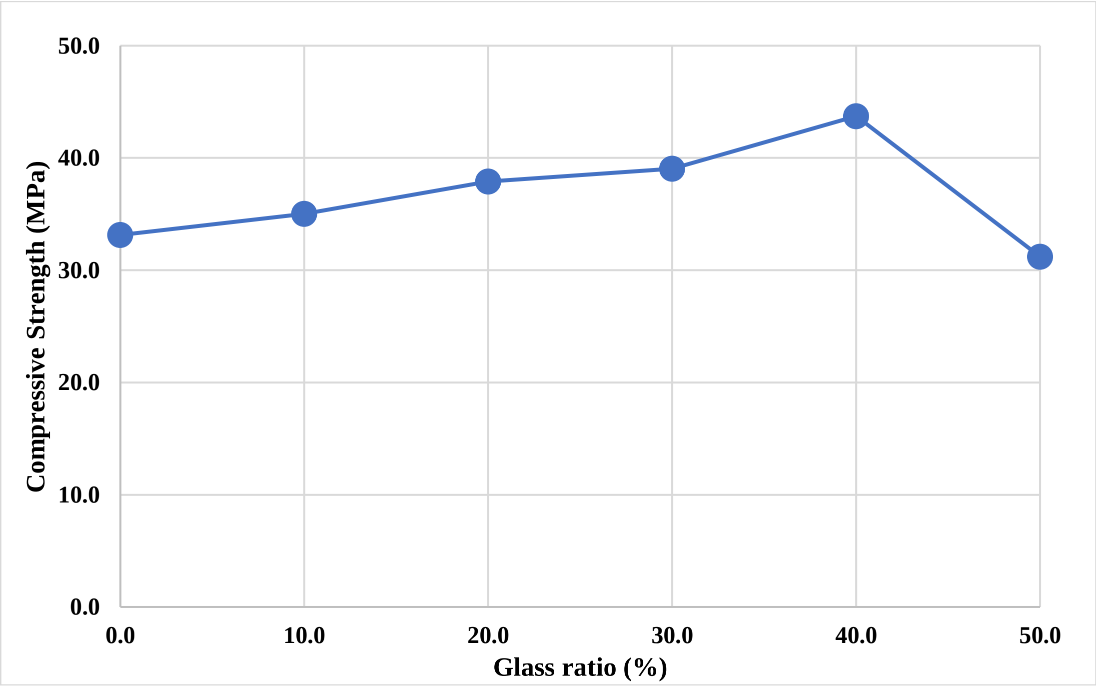

Fig. 10. Concrete's compressive strength as a result of different CGA contents.

3.2 Splitting Tensile Strength

The results are shown in Fig. 11. The tensile strength of concrete is only 10% of its compressive strength, roughly. Polypropylene acts to prevent cracks in concrete. The best and highest strength is from mix five (40% CGA), which had a strength of 4.11 MPa (+41.24%), which can be set as the optimum mix, and it is the identity of the compressive strength of the same mix. Mix six (50% CGA), which is 2.94 MPa (+1.03%) about the same similar result as the reference mix (0% CGA). The results of mixes two, three, and four were 3.26 MPa, 3.55 MPa, and 3.80 MPa, respectively with percent achievements of +12.03%, +21.99%, and +30.58%, which were almost in a straight line toward the optimum value, which is the value between the control range and the optimum mix. The optimum glass ratio was established by Park et al. (2004) as %30 for splitting tensile strength due to the higher strength of CGA as compared to the natural coarse aggregate. In the current study, however, the CGA content was only 40%. Increasing the CGA content beyond 40% tends to decrease the strength toward the original value with no CGA content. This is due to a decrease in the strength of the binding between the surface of the waste aggregate and the cement paste, as well as a drop in the compacting factor when off-grade coarse aggregate is used instead. Similarly, the reason for the increase in compressive strength due to the presence of more angular particles can be applied up to a CGA ratio of 40%. Beyond that point, a further increase in CGA results in decreased tensile strength due to the smooth surface, leading to reduced bonding. According to Sohaib et al. (2018), adding PP fiber to concrete affects its strength and increases its splitting tensile

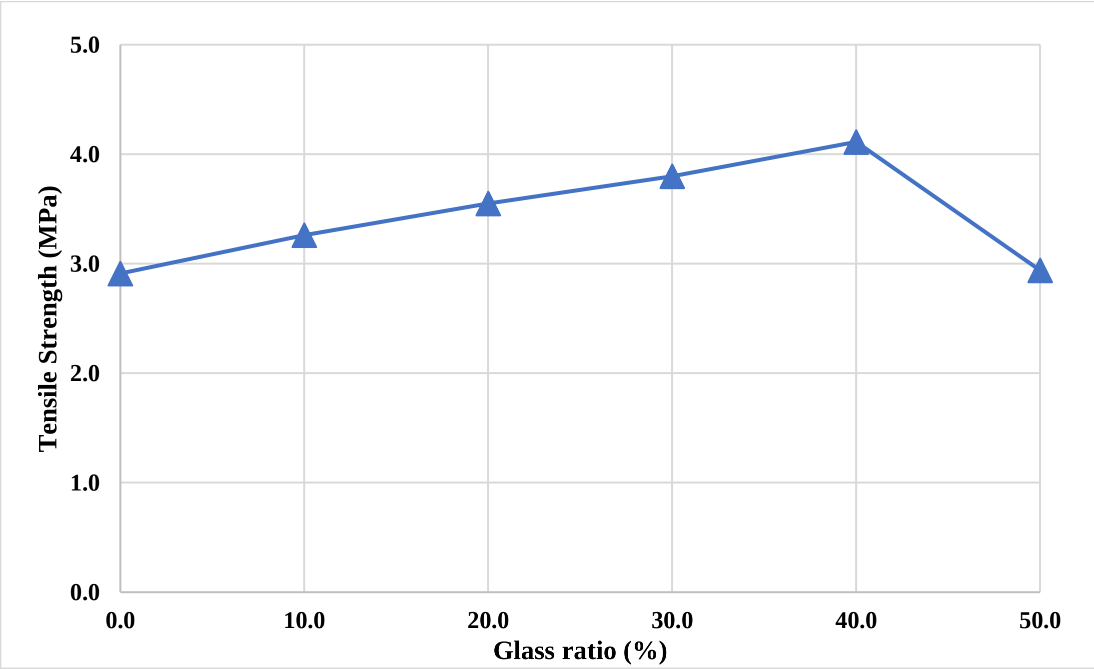

Fig. 11. Effect of different CGA content on Splitting tensile strength of concrete.

3.3 Flexural Strength

From Figure 12, mix one is for the control test of strength (2.68 MPa) with 0% CGA replacement. Mixes two, three, and four have flexural strengths (3.03, 3.24, and 3.54) MPa, respectively with +13.06%, +20.90%, and 32.09% improvement, respectively. Mix 5 has the best mix results (3.88 MPa) (+44.78%) and can be recorded as having the best CGA content because its compressive and splitting tensile strengths are both good. Mix five strengths (3.88 MPa) and +44.78%. After that, with an extra amount of CGA replacement with gravel, the flexural strength tends to decline to 3.00 MPa and +11.94%. Polypropylene increases ductility makes bonds more substantial and prevents cracks. In this study, 40% was established as the optimum amount of CGA content. Conversely, according to Park et al. (2004), the optimum glass ratio of flexural strength is 30%, the main reason being the decrease in adhesive strength between the surface of waste aggregate and the cement paste. Additionally, the percentage of CGA increases from 10% to 40% as a replacement for natural aggregate, there is a notable increase in flexural strength, as well as both the compressive and tensile strengths of the hardened concrete. Furthermore, the reduction in strength with increased CGA content up to 40% can be clearly seen, attributed to the formation of a weaker bond between the glass aggregates and the cement paste, as previously reported (Olofinnade et al., 2016).

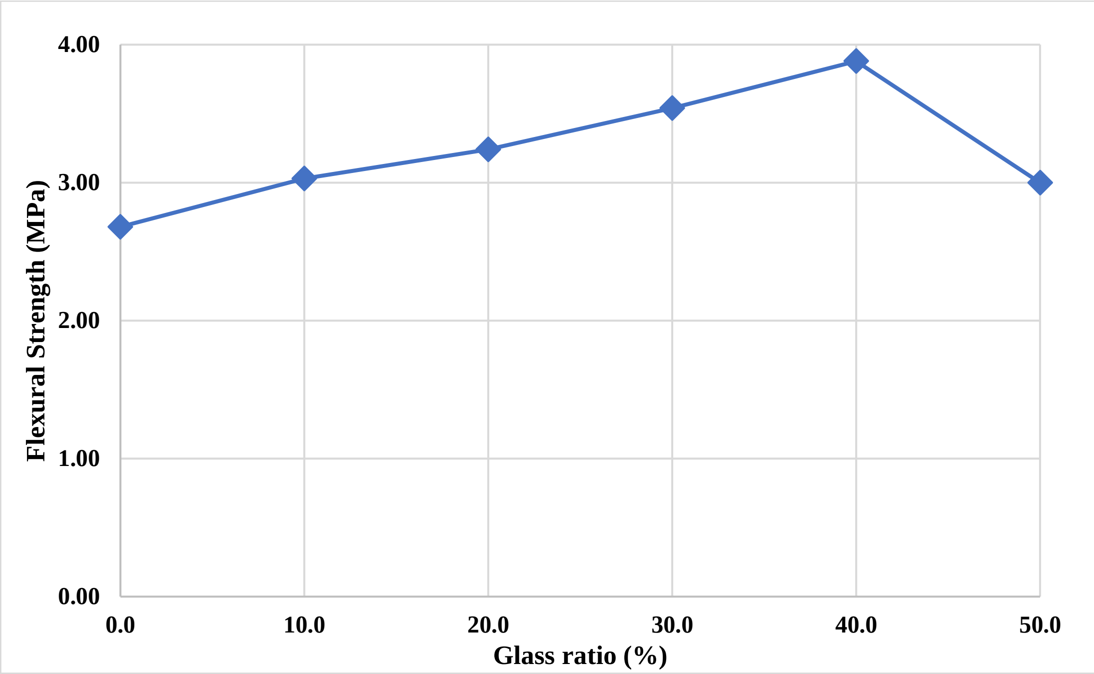

Fig. 12. Effect of different CGA contents on concrete's flexural strength.

4 ANALYSIS OF RESULTS

4.1 Compressive Strength versus Splitting Tensile Strength

Equation (1) for the relationship between splitting tensile and compressive strengths from Table 3, for CGA percent content as a replacement of natural gravel was calculated using the power trendline statistical model and is as follows:

$$f_{st} = 0.0604(f_c)^{1.1209} \qquad (1)$$

where:
f_c = compressive strength (MPa)
f_{st} = splitting tensile strength (MPa)

Eq. (1), seen in Fig. 13 as the blue-dotted curve, was created by substituting all of the CGA's percentage content for the natural coarse aggregate with a strong coefficient of determination ($R^2 = 0.9592$). For identity compression and splitting tensile strengths, this curve is contrasted with the ones that each individual CGA content represents. The curve depicts the anticipated splitting tensile strength based on the measured compressive strength for the tests performed for this study. According to the relationship, the splitting tensile strength should be approximately 9.5% of the compressive strength, which is comparable given According to estimates by Iskhakov and Ribakov (2021), concrete's tensile strength is equivalent to 10% of its compressive strength. Using Eq. (1), the splitting strength should be figured out if CGA is used instead of natural aggregate. This is because CGA tends to be more variable. The proposed equations were also compared to curves established for pervious concrete by Gaedicke et al. (2016), which had a very excellent and reasonable relationship.

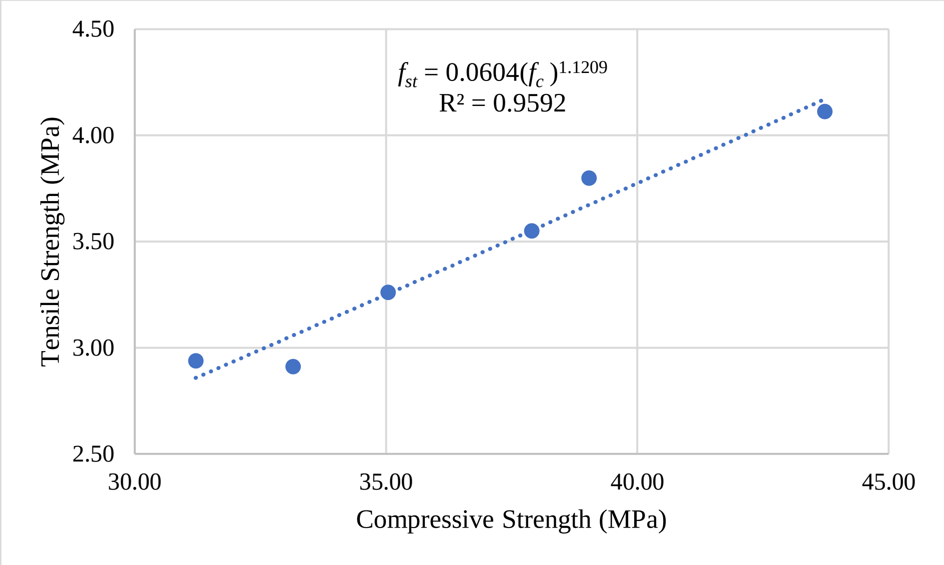

Fig. 13. Concrete with various CGA contents and its relationship between tensile and compressive strength.

4.2 Compressive Strength versus Flexural Strength

Using the power trendline in the statistical software, the following equation was created to represent the relationship between flexural strength and compressive strength from Table 3, for CGA percent content as a replacement for natural gravel:

$$f_r = 0.0994(f_c)^{0.966} \quad (2)$$

where:
f_c = compressive strength (MPa)
f_r = flexural strength (MPa)

Figure 14 shows Eq. (2) with R2 = 0.8417 as the blue-dotted curves of the relationship between flexural and compressive strength of concrete with different CGA content. This curve was made by replacing the natural coarse aggregate with the different percentages of the CGA contents. This curve's identity compression and flexural strengths are contrasted with those of each individual CGA content. Based on the measured compressive strength for the tests conducted for this inquiry, the curve displays the anticipated flexural strength. The connection states that the flexural strength should be around 8.75% of the compressive strength, which is an understatement given that normally the flexural strength of the concrete varies between 10 and 20 percent of its compressive strength depending on the kind, size, and volume of coarse aggregate employed (Association, 2000). It is not recommended to estimate the flexural strength of the concrete utilizing CGA in place of natural aggregate using Eq. (2) as it is, since it is below the lower limit of the estimated range.

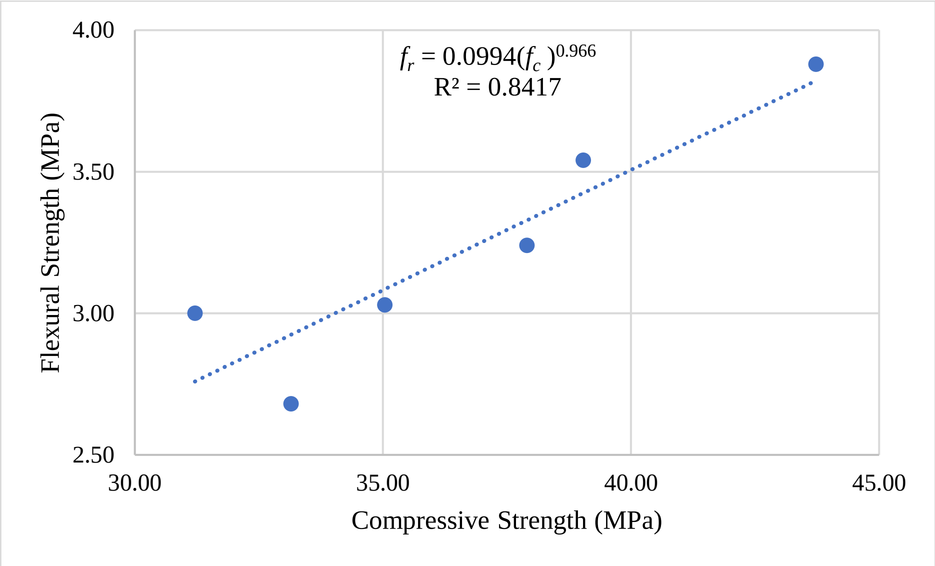

Fig. 14. Flexural and compressive strengths of concrete with varying CGA contents are correlated.

4.3 Splitting Tensile Strength versus Flexural Strength.

The correlation between the compressive and flexural strengths from Table 3, for CGA percent content as a replacement for natural gravel was represented by the following equation using the power trendline option in the statistical analysis software:

$$f_r = 1.067(f_{st})^{0.8986} \qquad (3)$$

where:

f_r = flexural strength (MPa)

f_{st} = splitting tensile strength (MPa)

The blue-dotted curve in Fig. 15, known as Eq. (3) with R2 = 0.9291, was produced by substituting the entire percentage content of the CGA for the natural coarse aggregate with R2 = 0.9291. This curve is compared to the tensile and flexure strengths that each CGA content represents for identity splitting. Based on the measured splitting tensile strength for the tests carried out for this investigation, the curve represents the projected flexure strength. Given that Maalej and Li (1994) estimated that flexural strength is equal to tensile strength, in the current work, the connection states that the flexure strength is roughly equivalent to 93.16% of the splitting tensile strength. Instead of flexural strength, this gap may be caused by Polypropylene's impact on the splitting tensile strength. The splitting strength should be calculated using Eq. (3) if CGA is used in place of natural aggregate. This is due to CGA's propensity for greater variability.

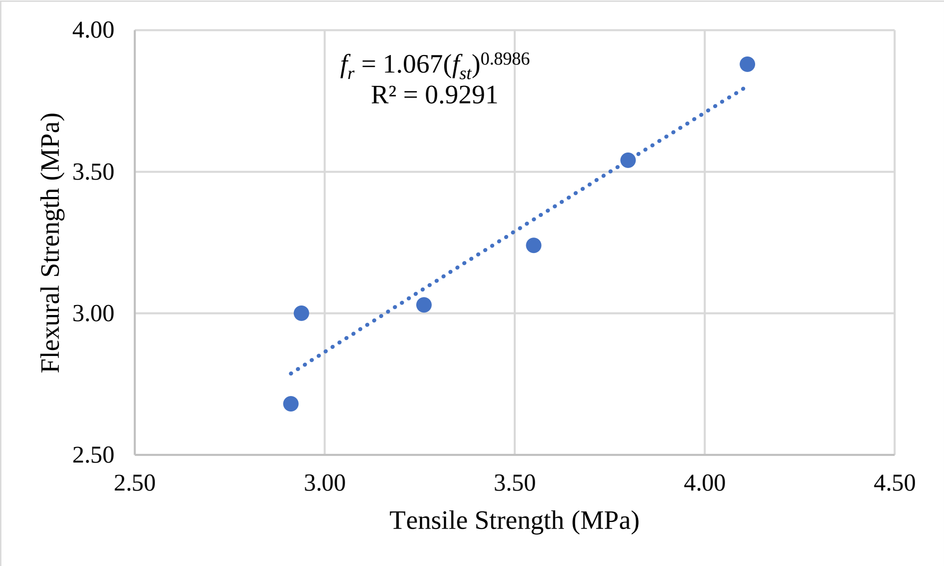

Fig. 15. Relationship between concrete's flexural and tensile strengths at various CGA contents.

5 CONCLUSIONS

The study delves into the noteworthy environmental and economic benefits of recycling crushed glass, driven by the substantial annual generation of glass waste. Its objective is to examine a viable method of using crushed glass to improve the mechanical properties of concrete, thus offering a sustainable solution for reutilizing this valuable resource. To achieve this, the mechanical characteristics of concrete amended with CGA and the addition of 0.2% polypropylene fibers were thoroughly examined. Various incremental CGA ratios ranging from 10% to 50% were tested, with increments of 10%. The following conclusion was drawn from the study.

- Increasing glass ratios, compressive, splitting tensile, and flexural strengths increased, peaking at an ideal of 40%. The compressive, splitting tensile, and flexural strengths were all higher at the 40% CGA content than in the control trial by 31,92%, 41.24%, and 44.78%, respectively that 40% CGA could be fixed as optimum content.

- Demonstrated that adding polypropylene fibers to concrete can increase its ductility, making bonds stronger, and avoid cracks while resolving concerns about brittleness. Additionally, the flexural and tensile strengths were notably improved with higher volumes of CGA usage. Despite glass being inherently brittle, the study found that the optimal values for compressive strength were attained at the same CGA ratio which is 40%.

- Determined that the proposed equations for predicting splitting tensile and flexural strength from compressive strength exhibited coefficient determinations of 0.96 and 0.84, respectively.

- Incorporating glass waste into concrete production, Long-term waste management solution can be achieved, simultaneously augmenting the mechanical properties of the concrete.

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