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Journal of Engineering Advancements Vol. 06(02) 2025, pp 41-47 https://doi.org/10.38032/jea.2025.02.002

Low-Carbon Concrete Development: Integrating Silica Fume, Glass Powder and Recycled Aggregates

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Received: April 10, 2025, Revised: June 17, 2025, Accepted: June 18, 2025, Available Online: June 22, 2025

ABSTRACT

Low-carbon concrete has an essential role in the reduction of the environmental impact of the building industry. Ordinary concrete manufacture is a significant contributor of carbon emissions due to high amount of energy that is needed in the processing of cement. The use of industrial by-products and recycled materials will offer a green solution to this problem. The research aims at exploring the use of silica fume (SF), waste glass powder (GP), and recycled coarse aggregate (RCA) as partial cement and natural aggregate replacements in developing eco-friendly concrete with reduced carbon footprint. A total of 16 concrete mixes (K0-K15) were designated with a mix ratio of 1:1:2 and a water-cement ratio of 0.45. Workability, compressive strength and tensile strength of different mixtures were tested. It was found that SF and RCA reduced workability because of the higher water demand, whereas GP increased it at low replacement levels, but the opposite happened at high GP contents e.g., in mix C30R100 (34 mm slump). The strength was significantly lowered by the porosity and poor bonding of RCA, but to a certain extent, SF countered this impact via pozzolanic responses. As an example, Mix C20R50 (20% cement replacement, 50% RCA) had about 85% of the strength of the control mix (C0) with 90 mm slump and 28-day compressive strength of 39.6 MPa, demonstrating that a reasonable trade-off between performance and sustainability is possible. A right combination of these materials may facilitate sustainability without compromising the structural performance. Mix C20R50 attained the best balance and showed better strength retention and reasonable workability without chemical admixtures. The study contributes to low-carbon concrete technologies by promoting the use of industrial byproducts, and recycled materials in construction.

Keywords: Low-carbon concrete, Recycled aggregate, Silica fume, Glass powder, Sustainable construction.

1 Introduction

Concrete is by far the most commonly used construction material in the world, whose annual consumption exceeds 100 billion cubic meters [1]. Nonetheless, its widespread application also causes significant problems to the environment, with cement production alone accounting up to 5.2 percent of global CO_2 emissions. Cement has a large carbon footprint, which is attributed to its manufacturing mechanism, primarily, the formation of clinker, which requires extremely high temperatures [2]. Due to growing environmental awareness; researchers and engineers are trying to find alternative materials that can reduce the use of cement in concrete without reducing and preferably increasing its performance. Partial replacement of cement by supplementary cementitious materials (SCMs) like silica fume, blast furnace slag, fly ash, and glass powder is one of the effective methods that can be used to reduce cement content. Such materials not only help reduce the environmental impact of cement production but also help to increase the life span and strength of concrete [3]-[5]. With the addition of SCMs, the microstructure of concrete is altered, with the improvement of the interfacial transition zone (ITZ), reduction in porosity, and enhancement of mechanical properties [6],[7]. Therefore, the use of SCMs in concrete is not only environmentally friendly, but also provides technological benefit in construction practice.

Most of the studies have analyzed SCMs individually whereas this study delves into the collective integration of silica fume, glass powder, and recycled aggregates, which is not largely reported. What is new is the combination of the three materials to achieve higher sustainability and mechanical behavior [3]-[5]. A comparative study is used to determine the comparison of this triad to the traditional SCM combinations like silica fume and RCA or glass powder exclusively [6],[7].

Silica fume is a by-product of the silicon and ferrosilicon alloy industry which is highly pozzolanically reactive. It consists of ultra-fine, spherical particles that are predominantly composed of silicon dioxide (SiO_2), consisting of which it is highly effective in enhancing the characteristics of concrete [8]. Silica fume is more reactive than other SCMs, such as fly ash and blast furnace slag, which enables small dosage levels to provide significant performance advantages [9]. The ultrafine particle size of silica fume which is approximately 100 times finer than cement is important in enhancing the concrete properties. Because of its large surface area, it effectively fills the voids in the cement paste resulting in a denser and compact microstructure [10]. This decrease in porosity strengthens the ITZ which is the interphase layer between aggregate and the cement matrix therefore enhancing the overall mechanical properties. Concrete gains high compressive and tensile strength, improved resistance to chloride penetration, and reduced permeability by incorporation of silica fume, factors that lead to its durability over time [11]. Besides the increase in physical properties, silica fume can react with calcium hydroxide (C-H) produced in the cement hydration process. The process leads to the formation of more calcium silicate hydrate (C-S-H) which is the primary binding component in concrete. Increased C-S-H concentration contributes to the early-age strength gain and contributes to the long-term durability [10]. Due to its enhanced pozzolanic activity, silica fume is largely used in high

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performance concrete where enhanced mechanical and durability properties are desired.

Recycling of waste glass into concrete has been given huge attention in the recent years due to its economic and environmental advantages [12]-[15]. Glass powder, which is produced by thoroughly grinding waste glass, possesses physical and chemical attributes similar to SCMs like fly ash and silica fume [16]. Use of glass powder in concrete not just offers a feasible recycling option to waste glass but also offers sustainability in the construction industry.

Although it can be advantageous, the use of glass powder as a replacement of cement has had a restricted reception through the concerns of alkali-silica reaction (ASR). Glass aggregates contain high alkalis levels that may react with silica in cement and lead to expansion, thus resulting to cracking and durability issues [17]. Nevertheless, research has shown that pulverizing waste glass may reduce the ASR-related problems as well as increase the pozzolanic activity of the material [18]. It has been found that using glass powder as a partial replacement of cement (up to 30 wt.%) can reduce the ASR expansion, without or increasing the compressive strength [19]. Also, crushed glass powder exhibits a higher pozzolanic activity, further enhancing the microstructure of concrete and increasing its mechanical properties [20]. In addition to the mechanical performance, glass powder has been demonstrated to increase fresh-state properties including workability. Research has also shown that the addition of glass powder can increase flowability without the need of additional superplasticizers, and is therefore beneficial in the use of high-performance concrete [21]. Moreover, one of the studies showed that the use of glass powder as a cement substitute does not have a considerable effect on the durability related characteristics [22]. Consequently, glass powder is a viable substitute to regular cement, aligning with sustainability goals, including the RE2020 environmental law.

Due to the problem of decrease in natural aggregates, the construction sector has been resorting to recycled concrete aggregates (RCAs) to a larger extent. Nevertheless, there is no proper emphasis on the recycling of construction and demolition (C&D) waste in international regulations at present, which disrupts large-scale implementation [13]. Since it was first used in Germany, post-World War II studies demonstrated the promise of RCAs in making sustainable concrete. The RCAs are not similar to naturally occurring aggregates due to the attached cement mortar that leads to larger porosity, higher water absorption, and poor mechanical properties [9]. This unhydrated mortar makes ITZ weak, which results in reduced compressive and tensile strength [9]. Experiments prove that the compressive strength of concrete with 100% RCA is lower by 20 25 % after 28 days in comparison with normal concrete (w/c = 0.50, cement content = 325 kg/m^3) [6]. Nevertheless, the implementation of RCA of high-strength concrete (50 MPa) can contribute to reducing such losses in strength. In order to enhance the mechanical properties of RCA-concrete, the addition of silica fume has been useful. The inclusion of silica fume pozzolanic reaction helps in strengthening ITZ in order to offset the lower strength developed due to RCA inclusion [11]. It has also been shown that washing RCAs prior to use can enhance their properties through decreasing porosity and increasing strength [6].

The essence of the study is to determine the synergistic effect of silica fume, glass powder, and recycled aggregate on mechanical and fresh properties of the concrete. Precisely, the research hypothesizes to determine the effectiveness of these materials in compressive strength, split tensile strength, and workability as partial cement and natural coarse aggregate replacements. This study attempts to develop an ecologically sustainable concrete mix design by maximizing the replacement rates that will reduce cement content, limit the use of natural aggregates and optimize the overall performance. The outcomes will be used to promote the development of sustainable construction methods as the study will provide information on the potential to use such alternative materials in structural works. Besides, the incorporation of these materials addresses the international pressure of reducing carbon emission in the building sector [2]-[5].

2 Materials and Methodology

2.1 Cement

A locally obtained standard Portland cement of CEM I 42.5 grade is applied. Standard Portland cement conforms with E.S.S. 4756-1/2013 CEM I 42.5N and BS EN 197-1:2011 CEM I 42.5N. The fineness of cement is 3390 cm²/g, and its specific gravity is 3.15, as per ASTM C204 and ASTM C187, respectively. The chemical composition of waste glass powder, silica fume, and cement is shown in Table 1.

2.2 Silica Fume

The employed silica fume is a hydraulic mixture of active components including fine latently reactive silicon dioxide of 0.1 μm in size (Sika Fume, 2020). Silica fume fulfills the standards of ASTM C1240. Fineness and specific gravity of the silica fume are 19500 cm^2/gm and 2.23 according to ASTM C204 and ASTM C187, respectively. Fig. 1 depicts the look of employed silica fume.

(a) (b)

Fig. 1 (a) Silica fume and (b) waste glass powder

2.3 Waste Glass Powder

The glass powder was recovered from glass debris that was given by the Badda (Bangladesh) local waste disposal facility. In order to make the glass powder, the collected waste glass wFas first cleansed of any pollutants by soaking it in water for seven days. The water was changed every day throughout this time. Following cleaning, the crushing process was repeated until the glass powder had a diameter of less than 75 μm, which allowed it to pass through a NO. 200 sieve. According to the previously established ASTM requirements, the waste glass powder's fineness and specific gravity are 3870 cm^2/gm and 2.55, respectively. The look of discarded glass powder is depicted in Fig. 1.

2.4 Aggregate

Sand is employed as the fine aggregate in this study, whilst crushed dolomite is used as the coarse aggregate. Sand and crushed dolomite underwent sieve analysis tests in conformity with ASTM C136. Sand has a fineness modulus of 2.65 and a specific gravity of 2.11. The fineness modulus of crushed dolomite is 7.66, its specific gravity is 2.52, and its nominal maximum size is 20 mm.

2.5 Recycle Aggregate

The recycled concrete aggregates, which have a target strength of 60 MPa, are created from precast concrete rejects that are transported through an industrial crushing process. LNEC E 471 standard [23] (Table 2), which states that the recycled coarse aggregates (the sole fraction taken into consideration) must have a density higher than 2200 kg/m^3 and a water absorption below 7%, was met by the RA.

Table 1 Chemical composition of cement, silica fume, and waste glass powder

Oxide (%)	**Chemical Composition (%)**		
	Ordinary Portland cement	**Silica fume**	**Waste glass powder**
SiO_2	21.08	95.67	70.45
CaO	63.12	0.13	10.89
Al_2O_3	4.86	0.23	2.03
Fe_2O_3	4.43	0.37	0.52
SO_3	3.03	0.22	0.37
MgO	1.47	0.22	2.40
Na_2O	0.24	0.11	11.31
K_2O	0.43	0.18	0.78
L.O.I.	1.34	2.87	1.25

Table 2 Properties of the coarse aggregates and recycle aggregate.

Property	**Condition**	**Aggregates**	
		Natural	**Recycle**
Particle density (g/cm³)	Oven-dry particles	2.63	2.34
	Saturated surface-dry	2.66	2.48
Water absorption (%)	-	1.9	5.8
Specific gravity	-	2.52	2.40
Fineness modulus	-	7.66	6.88

With a water-to-cement ratio (w/c) of 0.45, the concrete mix design corresponds to a 1:1:2 ratio (cement: fine aggregate: coarse aggregate). A total of sixteen mix variations (K0–K15) were constructed, with various percentages of natural aggregate replacement (50–100%) with recycled aggregate and cement replacement (10%–30%) with silica fume and glass powder. 491.2 kg/m³ of cement, 491.2 kg/m³ of fine aggregate, and 982.4 kg/m³ of natural coarse aggregate were all included in the control mix (K0) as shown in Table 3. In modified mixes, recycled aggregate was utilized at 50%, 75%, and 100% replacement levels for natural aggregates, while silica fume and glass powder were added in proportions of 5%, 10%, and 15% to partially replace cement as shown in Table 4. Every mix was constructed to retain the desired workability and strength while assuring consistency in the aggregate volume and total binder content. ASTM C192 was followed in the preparation, casting, and curing of concrete mixes. In line with ASTM C143, the slump test was utilized to evaluate the concrete mixtures' workability. At 7 and 28 days, 150 mm × 300 mm cylinder specimens were cast for testing of split tensile strength (ASTM C496) and compressive strength (ASTM C39). The photographs taken during the test are given in Fig. 2.

Table 3 Percentage of replacement

MIX	Mix Designation	Cement Replacement (%)	Natural Aggregate Replacement (%)	Silica Fume (%)	Glass Powder (%)	Recycled Aggregate (%)
MIX 1	C0	0	0	0	0	0
MIX 2	C10	10	0	5	5	0
MIX 3	C20	20	0	10	10	0
MIX 4	C30	30	0	15	15	0
MIX 5	C0R50	0	50	0	0	50
MIX 6	C10R50	10	50	5	5	50
MIX 7	C20R50	20	50	10	10	50
MIX 8	C30R50	30	50	15	15	50
MIX 9	C0R75	0	75	0	0	75
MIX 10	C10R75	10	75	5	5	75
MIX 11	C20R75	20	75	10	10	75
MIX 12	C30R75	30	75	15	15	75
MIX 13	C0R100	0	100	0	0	100
MIX 14	C10R100	10	100	5	5	100
MIX 15	C20R100	20	100	10	10	100
MIX 16	C30R100	30	100	15	15	100

(a) (b) (c)

Fig. 2 Testing procedure: (a) all materials of the study, (b) compression test, (c) split tensile test

Table 4 Concrete mixes proportion.

Mix Designation	Cement Replacement	Natural Aggregate Replacement (%)	Cement (kg/m^3)	Silica Fume (kg/m^3)	Glass powder (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate	Recycled Aggregate	W/C
C0	0	0	491.2	0	0	491.2	982.4	0	0.45
C10	10	0	442.08	24.56	24.56	491.2	982.4	0	0.45
C20	20	0	392.96	49.12	49.12	491.2	982.4	0	0.45
C30	30	0	343.84	73.68	73.68	491.2	982.4	0	0.45
C0R50	0	50	491.2	0	0	491.2	491.2	491.2	0.45
C10R50	10	50	442.08	24.56	24.56	491.2	491.2	491.2	0.45
C20R50	20	50	392.96	49.12	49.12	491.2	491.2	491.2	0.45
C30R50	30	50	343.84	73.68	73.68	491.2	491.2	491.2	0.45
C0R75	0	75	491.2	0	0	491.2	245.6	736.8	0.45
C10R75	10	75	442.08	24.56	24.56	491.2	245.6	736.8	0.45
C20R75	20	75	392.96	49.12	49.12	491.2	245.6	736.8	0.45
C30R75	30	75	343.84	73.68	73.68	491.2	245.6	736.8	0.45
C0R100	0	100	491.2	0	0	491.2	0	982.4	0.45
C10R100	10	100	442.08	24.56	24.56	491.2	0	982.4	0.45
C20R100	20	100	392.96	49.12	49.12	491.2	0	982.4	0.45
C30R100	30	100	343.84	73.68	73.68	491.2	0	982.4	0.45

3 Results and Discussion

3.1 Workability

Slump test results indicated a high decrease as cement replacement (GP, SF) and natural aggregate replacement (RA) increases. The results ranged between 90 mm (C0) and 34 mm (C30R100) as illustrated in Fig. 3.

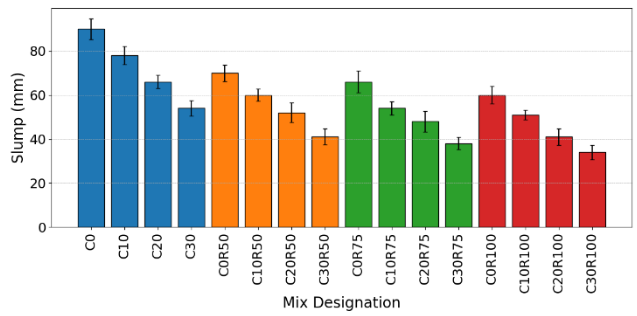

Fig. 3 Workability of different mix designations

The 10%, 20%, and 30% GP-SF replacement mixes (C10-C30) noticed a reduction of 78 mm, 66 mm, and 54 mm, respectively, although the 0% replacement control mix C0 had the largest decline (90 mm). The increased fineness and water absorption of SF compensates the increased workability of GP due to reduced water consumption [24]. Mix C0R50 (50% RA, no GP-SF) experienced a 70 mm drop, dropping even more in C0R75 (75% RA: 66 mm) and C0R100 (100% RA: 60 mm). As in previous research, the combination was stiffened by the rough texture and high water absorption of RA [25].

C30R100 showed the lowest drop (30% GP-SF + 100% RA: 34 mm), indicating that the high SF and RA content has a significant negative effect on workability. Mix C30R75 (30% GP-SF + 75% RA: 38 mm) was used to support this design. SF and RA increase water consumption and paste viscosity, whereas GP enhances workability [26]. Due to their coarse texture and higher water requirement SF and RA disrupt workability compared to GP which improves workability. It is however necessary to explain that the enhancement of workability by GP is merely realized at low-to-moderate replacement levels. Even at high GP content, i.e., in Mix C30R100, the workability decreases strongly. This is consistent with the data at hand and helps to substantiate the claim that GP improves workability [24],[26] but merely to such an extent that the fineness and reactive surface of SF and the porosity of RA do not become controlling factors with respect to the mix behavior.

C0 (90 mm) registered the best slump whereas C30R100 (34 mm) recorded the worst. GP and SF should be balanced to become workable. High RA-SF mixes superplasticizers need to be investigated in the future [26]. These results support the earlier literature that although GP enhances fresh concrete properties in the early age, the effects of high SF and RA overwhelm the positive impacts at a certain threshold level [24],[25],[26].

3.2 Compressive Strength

The compressive strength decreases with the increase in the amount of the recycled coarse aggregate (RCA) in the concrete mixture as shown in Fig. 4. Mix C0R50 (50% RCA) exhibited a 16.4 percentage decrease in compressive strength after 28 days when compared to the control mix (C0). Mix C0R75 (75% RCA) and Mix C0R100 (100% RCA) further declined by 28.8 and 42.9 respectively. This trend is consistent with the previous studies, which indicate that RCA reduces compressive strength because of its porous structure, as well as the weaker interfacial transition zone (ITZ) between RCA and the cement paste [27]. The bond is weakened by the high absorption capacity of RCA, which absorbs cement paste and water, and the loss in strength increases with the increase in replacement level. Despite the fact that RCA can behave in a similar way as the natural aggregates when properly prepared, its fundamental deficiencies result in a weakened concrete matrix [27].

The loss of strength as a result of RCA is even complex when other materials are used together like the glass powder and silica fume which have varied effects on the microstructure of the cement matrix [27]. This type of complicated interactions is especially pronounced in the mixes containing high proportion of RCA like C30R75 and C30R100, in which the strength of the mixes decreases overall even with pozzolanic supplementation.

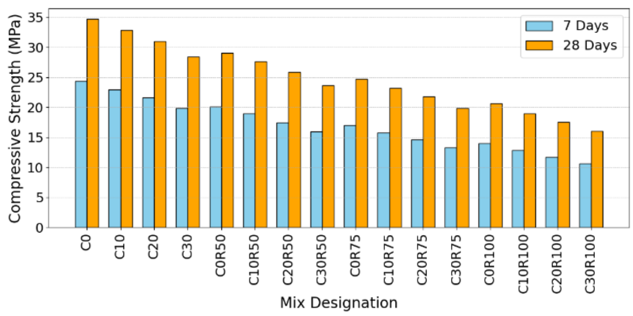

Fig. 4 Compressive strength of various mix designations

Compressive strength is also largely influenced by the use of waste glass powder (WGP) as a partial cement substitute. Mix C10 (5% WGP) suffered a 5.42 percent lag in 28-day compressive strength relative to the control mix. Mix C20 (10% WGP) and Mix C30 (15% WGP) disclosed greater reductions of 10.8 and 18.2, respectively. These results agree with those that show a slight strength increase with low replacement levels of WGP (up to 5%) but reduces at higher levels [28]. The reduced strength is attributed to non-porous smooth surface nature of glass particles that do not foster the bond between WGP and cement paste. In comparison with other supplemental cementitious materials (SCMs) such as silica fume or fly ash, WGP is less pozzolanically active, and thus less valuable in reinforcing strength [29].

The presence of WGP has greater impacts when accompanied by RCA since they both work toward creating a less bonding environment. Nevertheless, WGP effects can be different due to its percentage and interaction with SF in ternary systems [28],[29].

Silica fume (SF) increases compressive strength when used in mixes with RCA and WGP, because of its high pozzolanic reactivity. In cement, SF is mixed with calcium hydroxide (CH) to produce additional calcium silicate hydrate (C-S-H) gel, reinforcing the matrix. The effect of SF is especially evident in RCA-bearing mixtures, in which it increases the ITZ and reduces microcracks. As an example, the Mix C20R50 (50% RCA + 10% SF) demonstrated the greater ability to retain strength due to the pozzolanic impacts of SF. Even though the strength of Mix C30R75 (75% RCA + 15% SF) was lower than the strength of natural aggregate concrete, SF reduced the development of microcracks and enhanced the bonding between RCA and cement paste. These results align with those of an earlier study that reported that SF offsets the negative effects of RCA on compressive strength, particular at the latter curing ages [27].

To further visualize said trends, a side-by-side comparison of mixes with and without SF under identical RCA and WGP conditions affirms that, indeed, SF invariably increases compressive strength regardless of group [27].

Fig. 4 shows the pattern of compressive strength decreases with the 7 day and 28 day strength of various mix designations. The control mix (C0) shows the highest strength, and on further increasing the concentration of RCA and WGP, a sharp decrease is obtained. Also, the % change in compressive strength relative to C0 is demonstrated in Fig. 5. The scatter plot exemplifies the substantial reductions associated with more RCA and WGP replacements, and at the same time, indicates the cooling effect of SF. The 0% reference line simplifies the visualisation of the control mix deviations. This figure demonstrates the conclusion that although RCA and WGP lead to loss in strength, the pozzolanic reactivity of SF enhances overall concrete performance.

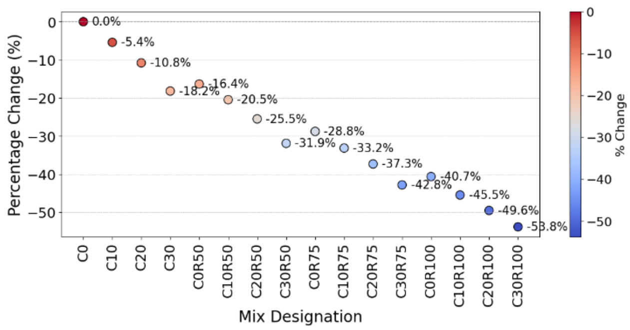

Fig. 5 Compressive strength percentage change respect to C0.

The effect of RCA, WGP, and SF together are more complex in terms of compressive strength. RCA induces some losses of strength, but WGP promotes this problem additionally due to its smooth surface and low reactivity. But SF is assisting in turning these downs around. As an illustration, Mix C10R50 (50% RCA + 5% SF) and Mix C20R50 (50% RCA + 10% SF) showed better strength retention in comparison with the identical mixes without SF. Even in Mix C20R50 (50% RCA + 10% WGP + 10% SF), as the strength was reduced SF increased the ITZ and minimized the micro cracks, improving the mixed performance. These findings suggest that the pozzolanic activity of SF ensures that the negative impact of RCA and WGP can be mitigated to some degree, leading to a longer-lasting concrete mix. These remarks once again confirm the observations in [27], that silica fume is especially useful in combinations where it would otherwise suffer greatly in performance because of RCA and WGP.

3.3 Split Tensile Strength

In this research, the effect of recycled aggregate (RA), silica fume (SF), and waste glass powder (WGP) was evaluated as a partial cement replacement by analyzing the results of the tensile strength of concrete mixes at 28 and 7 days. The information provided in the Fig. 6 obviously indicates that as the content of RA, SF, and WGP in the mixture increases, the tensile strength decreases.

The control mix (C0) tensile at 7 days was 3.22 MPa as compared to the mix that used the highest amount of replacements (C30R100) with a tensile of 1.87 MPa. This means that there was a decline in tensile strength by about 42 percent between maximum and minimum after 7 days. The same pattern was observed in the 28 day tensile strength where after the maximum strength a fall of 43 percent was observed between the highest and the lowest strength obtained after 28 days. The highest value was 3.69 MPa in the control mix (C0) and the lowest value was obtained in the mix with the most replacements (C30R100), which is 2.11 MPa. Such trends are accompanied by the findings of the previous research into the ways in which RA, SF, and WGP modify the characteristics of the concrete.

These components have been observed to have some impact on the mechanical properties of concrete and this has been dealt with in a number of research programs. Silica fume, e.g., has been shown to increase the mechanical strength of concrete by fillings micropores and increasing the bond between the concrete paste and the aggregates [27]. In just the same manner, use of recycled aggregates is likely to restrict the growth of early age strength due to the larger porosity and poorer bond of the aggregate-cement contact. Nevertheless, with the addition of materials in the form of additives such as silica fume steadily enhancing performance in the long term is possible through pozzolanic effects [30]. Even though it causes a decrease in performance when used in increased amounts, it has been noted that waste glass powder use can also increase the tensile strength, particularly at reduced replacement levels [29]. These observations [27],[29],[30] have led to the reason that the kneading proportions of materials need to be optimized according to the balance of reactivity, the microstructural packing, and the bonding at the interface in order to maintain the tensile performance.

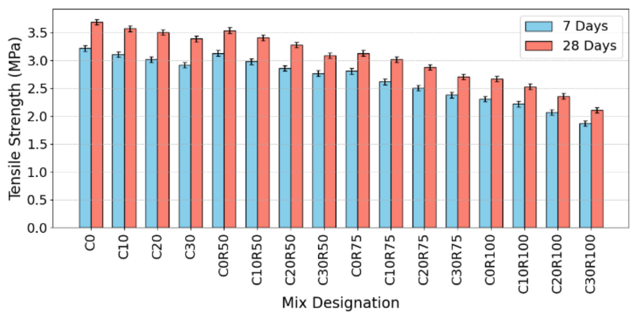

Fig. 6 Split tensile strength of diverse mix designations

In experiment, the addition of SF, RA, and WGP amounts to a reduction in the tensile strength of value at 7-days. Unlike in Mix C10 (10% SF) whose tensile strength was 3.02 MPa, Mix

C5 (5% SF) experienced much higher 7-day tensile strength (3.11 MPa). This is consistent in the findings of a study [29] where it is revealed that the tensile strength rose till 5% substitution of WGP and then began to decline. Similarly, the loss of strength as the recycled aggregate concentration increases conforms to the previous researches that have established that due to the poor quality of the recycled aggregate material compared to the native one, the deterioration in the mechanical properties is observed [29].

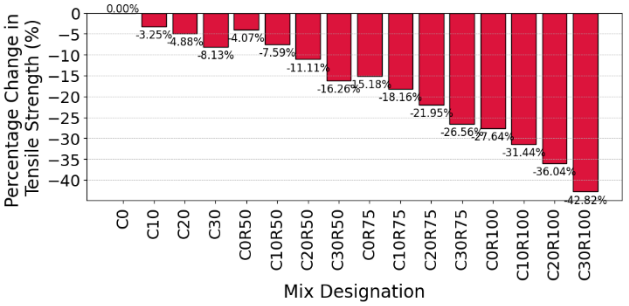

Fig. 7 The change of split tensile strength as a percentage of the split tensile strength at C0.

Fig. 7 illustrates the percentage change of the tensile strength held at 28 days with respect to every mix designation with regards to the baseline of the mix (labeled C0). The negative numbers reflect a decrease in tensile strength and the graphically displays the performance of the various mix variants against that of the reference mix with each bar labelled to indicate the exact % difference. Such a comparison informs on the way of the combination of various materials influences the tensile strength with time.

The 7-day tensile files as expected are lower than the 28-day strength with a higher percentage of strength gain being experienced between 7 and 28-days. This can be explained in line with the overall behaviour of concrete i.e., strength increases as it hydrates and in mixtures involving pozzolanic materials such as silica fume [30]. As opposed to recycled ones, though, aggregates are likely to reduce early-age strength development due to their increased porosity and misbonding, which makes the growth of tensile strength slower and less steep as the hydration process develops [30]. In general, the research results indicate the very complex interactions that take place when waste glass powder, silica fume, and recycled aggregates are included in concrete mixtures. Despite the prospect of an increased long-term strength, recycled aggregates and more extensive quantities of waste glass powder will extinguish the upsides of silica fume usage. To further put these findings in perspective, the trends in loss of tensile strength falls in line with trends discussed in compressive strength studies done in the past [27],[29],[30]. The one significant goal of subsequent research should be to optimize the attainability of the right balance of this combination of materials through workability, strength, and sustainability.

4 Conclusion

The objectives of this research work were to produce low-carbon concrete by partially substituting cement and natural aggregate with silica fume (SF), waste glass powder (GP) and recycled aggregate (RA). In order to determine the applicability of these materials in sustainable construction, the study determined their impact on workability, compressive strength and tensile strength.

It is evident in results that workability decreases with the increase in levels of SF and RA since SF is very fine and RA has rough texture, which would require more water. Nonetheless, GP enhances workability by a little bit, especially when used in lower SF and RA mixes. The compressive strength drops slowly as the proportion of RA and GP rise. Pozzolanic activity enhances the strength bonding between aggregates and cement paste thereby reducing the loss of strength unlike in the case of SF. Likewise, the tensile strength is dropping with an increase in the replacement levels; yet, the mixes with lower SF shows better performance in general.

The investigation proves that low-carbon concrete with acceptable mechanical performance can be composed by balanced SF, GP and RA with considerable attention paid. The mix found in the present study to give the optimum combination of retained strength and sustainability was the optimum mix of 20 percent SF and 50 percent RA. Further studies on the types of superplasticizers used to improve the workability of the high RA and SF mixes and the proportioning of the mixes to meet the onsite construction works should also be done. Additionally, other researchers ought to conduct an examination of the long-term functionality of these mixes in diverse environmental settings to have a complete evaluation of their applicability in real life contexts. This study can help the broader world in curbing carbon emissions in the concrete industry and, at the same time, enhancing more environmentally sustainable construction materials.

Acknowledgement

We acknowledge the support of facilities from Dhaka International University, Dhaka, Bangladesh for this study.

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