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Research Article

Microstructural and mechanical properties evaluation of concrete with green glass powder

Haneen Kadhim[*,a], Ammar Muttar [b]

Civil Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

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Abstract

The growing amount of non-biodegradable solid waste, especially waste glass, is a major environmental issue. Simultaneously, the carbon footprint related to the production of cement is very high, and the creation of an alternative concrete technology needs to be developed in a sustainable way. The paper discusses the feasibility of partially replacing 10%, 20%, and 30% of cement weight with green glass powder alongside 1% superplasticizer to produce sustainable concrete. The novelty of the research lies in the fact that the entire correlation between mechanical properties and microstructural behavior is revealed, with particular emphasis on the densification of the matrix and the refinement of the interfacial transition zone. Experimental program involved compressive strength, splitting tensile strength, dynamic modulus of elasticity, and scanning electron microscopy tests. The findings indicated that the glass powder significantly enhanced the mechanical properties up to the optimal replacement level of 20% at the age of 28 days. The overall performance of the G20%-HRWRA mixture was the best, with a compressive strength of 58 MPa, a splitting tensile strength of 5.05 MPa, and a dynamic modulus of elasticity of 41 GPa, which was an increase of 30.34%, 67.00%, and 14.21%, respectively, compared with the reference mixture. SEM observations indicated that there was a highly dense cementitious matrix that had low-calcium hydroxide content and a refined ITZ. Overall, the findings show that incorporating 20% green glass powder and 1% superplasticizer is a sustainable solution for producing concrete.

1. Introduction

The rapid growth of the construction industry has significantly increased the demand for conventional concrete, resulting in intensive consumption of natural resources and increased environmental impacts [1]. Around 5–8% of the global CO_2 emissions are contributed by Portland Cement Manufacturing [2]. Therefore, it is important to minimize the cement use in concrete production by using Sustainable Supplementary Cementitious Materials (SSCM) to reduce the negative environmental effects of cement production without compromising its engineering properties. Considering the above discussed alternatives, use of industrial and municipal waste materials has gained significant attention as it can not only help to reduce the use of virgin raw materials but also help to reduce waste disposal problems [3, 4]. Waste glass is one of the most promising materials that could be recycled because of the high content of silica, abundance, and that glass does not decompose. A significant amount of waste glass is thrown annually into the landfill, which poses severe environmental landfill challenges. The recycling of this waste as finely ground green glass powder not only saves waste from landfills, but also partially substitutes Portland cement, thus reducing the CO_2 emissions and increased sustainability in concrete production [5, 6]. Green glass powder, when ground to a particle size of less than 45 µm, exhibits high amorphous silica content and high pozzolanic activity [7]. It reacts with calcium hydroxide

*Corresponding author: haneen.jwad@uomustansiriyah.edu.iq
[a]orcid.org/ 0009-0008-6615-1756; [b]orcid.org/ 0000-0002-5939-6148
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(CH) liberated during the hydration of the cement producing extra calcium silicate hydrate (C–S–H), which makes the cementitious matrix more compact and with better pore structure [8]. The small particles also have a micro-filler effect by filling micro-voids and smoothing the interfacial transition zone (ITZ) which is generally regarded as the weakest part of the conventional concrete [9-11]. Thus, the improvement of ITZ results in better mechanical performance because of the better bond between cement paste and aggregates. Apart from its microstructural characteristics, green glass powder can also have beneficial effects on the workability of fresh concrete due to relatively smooth surface texture and low water absorption as compared to the traditional pozzolanic materials [12, 13]. These benefits are even more significant when using green glass powder with high-range water-reducing admixtures (HRWRA) to deliver the desired workability whilst minimizing water needs and improving the concrete's microstructure [14-17].

Recent research has shown that both high-range water-reducing admixtures (HRWRA) and waste glass powder can have a significant impact in enhancing the performance of concrete and in promoting sustainable concrete. According to previous investigations HRWRA's optimum dosage usually falls in between 0.8% and up to 2%, to the curing age and the concrete composition. Omer et al. [18] reported the performance of 1% HRWRA to be best at early ages and improved at higher dosage at later age. However, Alsadey and Omran [19] discovered that the optimum dosage was 0.8% HRWRA, which demonstrates that the optimal dosage is dependent on the properties of the concrete mix. Likewise, many research works have validated the possibility of using green glass powder as a sustainable source of supplementary cementitious material. Most researchers believe that partial replacement rates on the order of 15–20% yield substantial gains in mechanical properties with a corresponding decrease in the use of cement and environmental effects. Many different partial replacement levels have been used and investigated by various studies, and they range from 15 to 35%. The pozzolanic reaction effect of the finely ground glass powder have been credited for these improvements [12,16,20-23]. However, variations in the optimum replacement levels have been reported due to differences in particle size, glass type, mixture proportions, and curing conditions. The individual effects of green glass powder and HRWRA on mechanical and microstructural properties of concrete, as well as the reduction of cement usage, recycling of waste glass, and mitigation of CO_2 emissions have been well established, but there is limited research into their combined effects on mechanical and microstructural properties while simultaneously addressing environmental sustainability concerns. Hence, the present study investigates the synergistic effect of replacing 10 %, 20 % and 30 % green glass with 1 % HRWRA to the concrete to obtain the optimum sustainable concrete mixture. Advantageously, the use of waste green glass powder as a partial cement replacement can not only divert the green glass wastes from landfills but also reduce the consumption of Portland cement and hence CO_2 emissions, and improve the mechanical and microstructural properties of the concrete due to the pozzolanic activity of the waste green glass powder.

1.1 Research Significance

This study introduces an innovative method toward the development of sustainable concrete by combining 1% HRWRA with green glass powder at ratios of 10%, 20%, and 30% as a replacement by weight of Portland cement. The current research builds on prior work that primarily focused on these materials individually and combines mechanical characteristics, microstructural analysis, and sustainability metrics into a unified experimental framework to determine the optimal mix ratio to minimize cement use, encourage glass waste recycling, reduce CO_2 emissions, and improve concrete performance.

2. Raw Materials

Sustainable concrete was produced using a mixture of Ordinary Portland Cement meeting IQS NO. 5, (2019) [24] with physical and chemical properties as presents in Table 1 and Table 2, fine aggregate with a maximum size of 4.75 mm according to IQS NO.45, (2021) [25], coarse aggregate with a maximum size of 12.5 mm according to IQS NO.45, (2021) [25], water conform with IQS 1703, (2018) [26], Superplasticizers or high-range water reducing admixture used in this study from the Sika company Viscorete-180 GS, according to ASTM C-494/C494M) [27], and green glass waste powder collected from glass juice bottles. Glass powder was prepared to function as supplementary cementitious materials due to the high silica content and potential pozzolanic reactivity.

The glass powder was cleaned of impurities, labels, and organic residues prior to crushing and grinding. The glass powder is ground until the particles pass the required sieve size according to the specification of ASTM C311, (2016) [28] leading to potential improvement in the mechanical and durability properties. Fig. 1 presents the X-ray diffraction analysis for green glass waste powder, and Fig. 2 presents the process to get green glass powder with a size of 45 μm. The physical and chemical properties of waste glass powder are presented in Table 3 and Table 4.

Table 1. The physical properties of ordinary Portland cement

physical properties	Test result	Limit of I.Q. S NO.5-2019 [24]
Fineness (cm^2/g)	4026	≥ 2800
Initial setting time (min)	110	≥ 45
Final setting time (hr)	3.25	≤ 10
Compressive strength @ 3 days (N/mm^2)	23	≥ 20
Compressive strength @ 7 days (N/mm^2)	43	≥42.5
Stability %	0.036	≤ 0.8

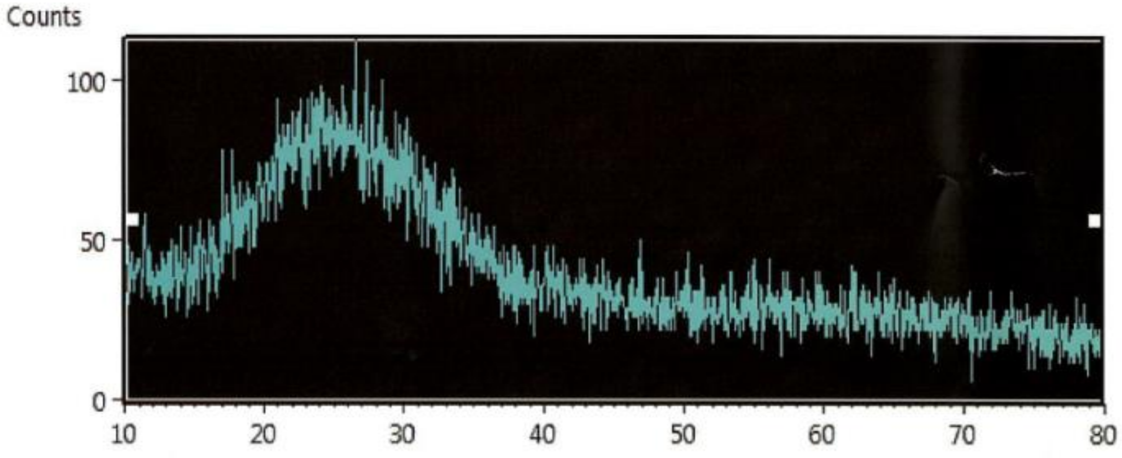


Fig. 1. X-ray diffraction analysis for green glass waste powder

Fig. 2. The process of producing green glass powder less than 45 μm

Table 2. The chemical properties of ordinary Portland cement.

Oxides Compositions	Weight %	Limit of I.Q. S NO.5-2019 [24]
L.O. I	2.815	≤ 4
SiO_2	18.87	-
Al_2O_3	5.4	-
Fe_2O_3	3.58	-
SO_3	2.33	≤2.5
CaO	63.89	-
MgO	1.84	≤5
Total	98.725	-
IR	0.51	-
CI-	0.078	-
C_3A	8.25	≤3.5(Sulfate Resistant Cement)

Table 3. The physical properties of waste green glass powder

Physical Properties	Test Result	Limit of ASTM C 618 2023 [29]
Specific Gravity	2.5	2.2-2.8
Fineness (Blain Method)	3416 Cm^2/gm	≥3000 Cm^2/gm
Bulk Density	985 Kg/m^3	800-1200 Kg/m^3

Table 4. The chemical properties of waste green glass powder

Oxide Composition	Oxide Content %	Limit of ASTM C 618 2023 [29]
SIO_2	72.00	-
AL_2O_3	5.01	-
Fe_2O_3	0.58	-
SO_3	0.90	≤4 %
CaO	13.79	-
Mgo	1.51	-
L.O.I	1.30	≤10 %

3. Mix Proportion

The design of mixtures was performed according to the Building Research Establishment method. A compressive strength of 40 MPa was the target for all mixes at 28 days. The water to cement ratio (w/c) of the reference concrete mixture was set to 0.4 to obtain the desired slump of 100 ± 5 mm. The optimum HRWRA dosage of 1% by weight of binder was selected based on its ability to achieve the maximum water reduction while maintaining the target slump, as presented in Table 5 and Fig.3.

Table 5. Water reduction of concrete mix for various dosages of HRWRA

Dose of HRWRA% by weight of cement	w/c to obtain100 ±5 mm slump	Slump mm	Water reduction %
0	0.4	95	-
0.5	0.38	100	5
0.6	0.375	101	6.25
0.7	0.37	99	7.5
0.8	0.36	97	10
0.9	0.35	100	12.5
1.0	0.32	103	20
1.1	0.32	102	20

The other mixes contained green glass powder with ratios of (0, 10, 20, and 30) % as a replacement for cement and 1% HRWRA to prepare specimens with sizes fitting the facilities and molds available in the laboratory, and were thought appropriate for both the material properties and aggregate grading employed during the experimental program. Cement and waste glass powder were mixed, then remixed with sand and aggregate for 1.5 minutes. Water and superplasticizer were added to the mixture, then mixed for 2 minutes to ensure the mixture achieves homogeneity. The operation was continued up to 5 minutes to ensure that the pozzolanic material was thoroughly dispersed between cement particles. All specimens were cured for 28 days in water tank (tap water) at approximately 23 ± 2°C. The proportions of concrete mixtures are presented in Table 6.

Table 6. Proportions of concrete mixtures

Code	MIX				HRWRA % by wt. of cement	Glass powder % by wt. of cement	Total Binder	w/cm 100±5mm slump	Slump mm	Water reduction %
	Cement kg/m³	Sand kg/m³	Gravel kg/m³	W kg/m³						
R	550	610	951	219	-	0	550	0.4	95	-
HRWRA	550	610	951	176	1	0	550	0.32	103	20
G10%-HRWRA	495	610	951	173.25	1	10	550	0.35	100	12.5
G20%-HRWRA	440	610	951	132	1	20	550	0.3	102	25
G30%-HRWRA	385	610	951	115.5	1	30	550	0.3	100	25

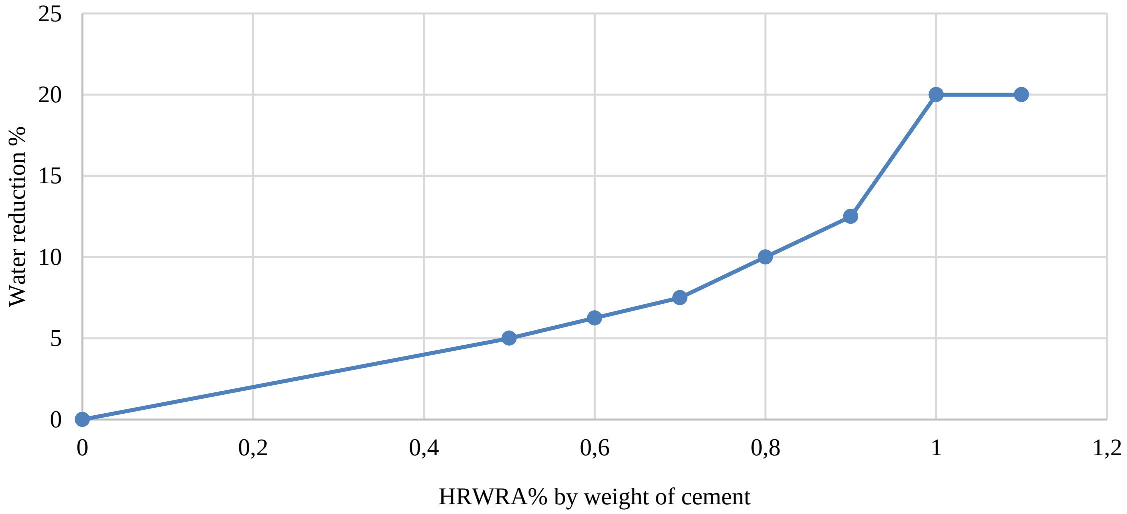


Fig. 3. Effect of HRWRA dosage on the water reduction of concrete

4. Results and Discussion

The results from the experimental program of the five concrete mixtures are presented and discussed in the next section. A total of 15 cube specimens with dimensions of (100 × 100 × 100) mm were prepared for the compressive strength test, and 15 cylindrical specimens with dimensions of (100 × 200) mm were prepared for the non-destructive test of dynamic modulus of elasticity and subsequent splitting tensile strength test with 3 specimens for each mixture. The values reported are the average of the three specimens of each mixture. The choice of 100 mm cube molds was made due to the availability of the molds in the laboratories, the efficiency of the materials, and the fact that the maximum size of aggregate is 12.5 mm, which is within acceptable limits for concrete testing. All cylindrical specimens were prepared to the same dimensions (100×200) mm because all the mixtures were tested under the same conditions with the same specimen dimensions, the results are internally comparable but no size correction factor has been applied. The experimental results obtained are summarized in Table 7.

Table 7. The average results of three concrete specimens for each mix

Mix No.	Code	Compressive Strength MPa	Splitting Tensile Strength MPa	Dynamic Modulus of Elasticity GPa
1	R	44.5	3.024	35.9
2	HRWRA	50	4.203	37.1
3	G10%-HRWRA	55.4	4.78	38.9
4	G20%-HRWRA	58	5.05	41
5	G30%-HRWRA	40	3.8	36.85

4.1 Compressive Strength

The results of compressive strengths tests of the concrete specimens with dimensions of (100×100×100) mm at the age of 28 days are displayed in Table 7, according to BS 12390, (2019) [30]. Fig. 4 shows that the mechanical performances were significantly enhanced by the addition of superplasticizer and waste glass powder, the compressive strengths for the reference mix were 44.5 MPa and for modified mix (1 % superplasticizers) was 50 MPa, with an improvement of 12.36 %. This has only been possible due to the better dispersion of cement particles, reduced water needs, and better compaction, which all result in a denser microstructure as well as reduced internal voids particularly in the interfacial transition zone. It was also enhanced by the inclusion of the green glass powder in the mix to some extent as cement replacement, where mixes G10%-HRWRA and G20%-HRWRA achieved compressive strengths of 55.4 MPa and 58 MPa, respectively, which are an improvement of 24.49 % and 30.34 %, respectively of the reference mix. This measure confirms that fine powder of glass (passing 45 μm), reacting with calcium hydroxide to form additional C-S-H gel, is a viable pozzolanic content in boosting the densification of the matrix, fine pore structure, and inter-particle bonding, which is consistent with the findings of Ghadban et al. [31].

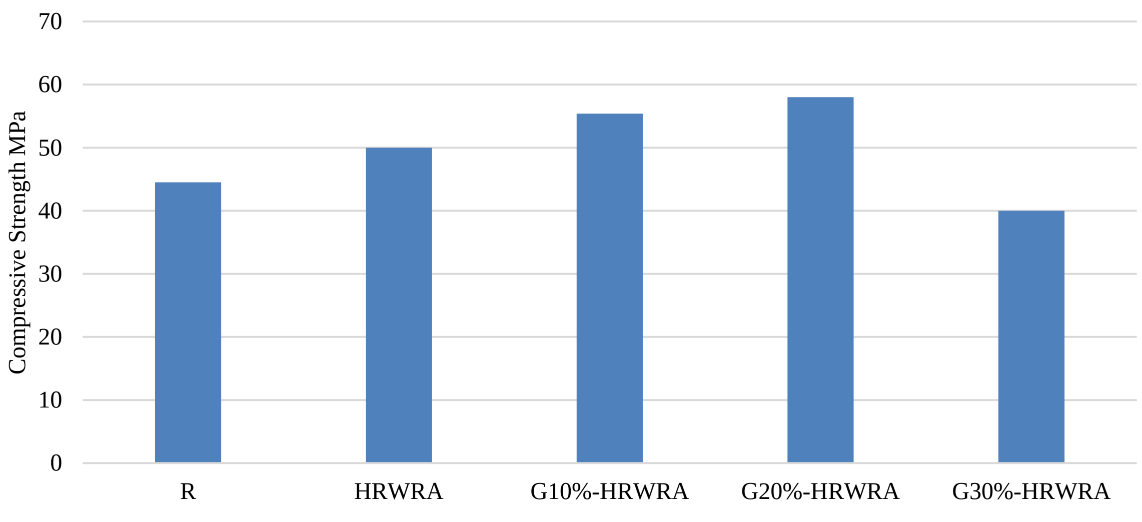


Fig. 4. The compressive strength results for the concrete specimens

Also, it is seen that the micro-filler effect increases the superiority of particle packing and reduces capillary porosity compared with previous studies that have recorded the optimum functioning of pozzolanic activity and packing density at a replacement degree of (10-20) %. However, compressive strength of mix G30%-HRWRA was observed to decline to 40 MPa, a 10.11 % drop compared to the reference mix. This reduction implies that the replacement level of 30 % is beyond the optimal level, in which the dilution effect will dominate since the effective content of cement decreases, and the hydration product required to develop the strength is not developed. The added powder of glass will still contribute to some clinker activity, but it cannot compensate the lower clinker content, so the microstructure will be less dense. Hence, the best mix (mix G20%-HRWRA) will be the one that has the largest improvement 30.34 % in comparison with the reference mix, and which has the largest compressive strength 58 MPa and consequently, the 20 % of improvement in replacement will be the best balance of the two aspects, sustainability, which is achieved by minimizing cement and the mechanical performance improvement. Fig. 5 displays the compressive strength test.

Fig. 5. The compressive strength test

4.2 Splitting Tensile Strength

The splitting tensile strength results presented in Table 7, according to ASTM C 496, (2017) [32], were obtained from the test performed on cylindrical specimens with dimensions of (100 × 200) mm, as shown in Fig. 6. The results display a similar trend with the compressive strength behavior, thus the effect of the use of both the superplasticizer and waste glass powder on the tensile performance of the concrete was beneficial, as in Fig. 7. The results for the reference mix were 3.024 MPa and for the modified mix (1 % superplasticizers) was 4.203 MPa, with an enhancement of 39 % when compared with the control mix. This is due to the fact that the superplasticizer has improved workability and the dispersion of the particle in the mix, which led to better compaction, lesser microcracking and increased ITZ, thus enhanced resistance to tensile stresses.

Fig. 6. The splitting tensile strength test

The mixes G10%-HRWRA and G20%-HRWRA were also found to improve more with the addition of the glass powder and attained 4.78 MPa and 5.05 MPa, respectively, which is 58.1 and 67 % better than the reference mix, respectively. These are attributable to the fact that the pozzolanic reactivity of the finely ground glass powder reacts with calcium hydroxide resulting in more C-S-H gel formation, resulting in a denser and more integrative microstructure. Micro-filler effect also increases the packing of the particles and minimizes the internal defects and starting point of the cracks, which play a significant role in development of tensile strength. It is proven that tensile strength is more refined to microstructure than compressive strength, which is why a higher percentage of the improvements is observed. Nevertheless, mix G30%-HRWRA also had a reduction in the splitting tensile strength to 3.8 MPa but this was still 25.7 % higher compared to the reference mix. This decrease against G20%-HRWRA shows that over replacement causes a dilution effect that results in a decrease in effective cementitious content and a decrease in bonding matrix that will adversely affect the resistance to cracks, this is in agreement with the findings of [33] On a micromechanical level, tensile response is regulated by the ratio between matrix densifying and binder reducing; when the ideal level is reached, the material becomes vulnerable to crack propagation. In this regard, mix G20%-HRWRA may be pointed to as the most suitable mixture in terms of splitting tensile strength, the highest result (5.05 MPa) and percentage of improvement (67) relative to the reference mix, thus, the 20 % level of replacement in terms of glass powder with 1 % of HRWRA is the most effective solution to the problem.

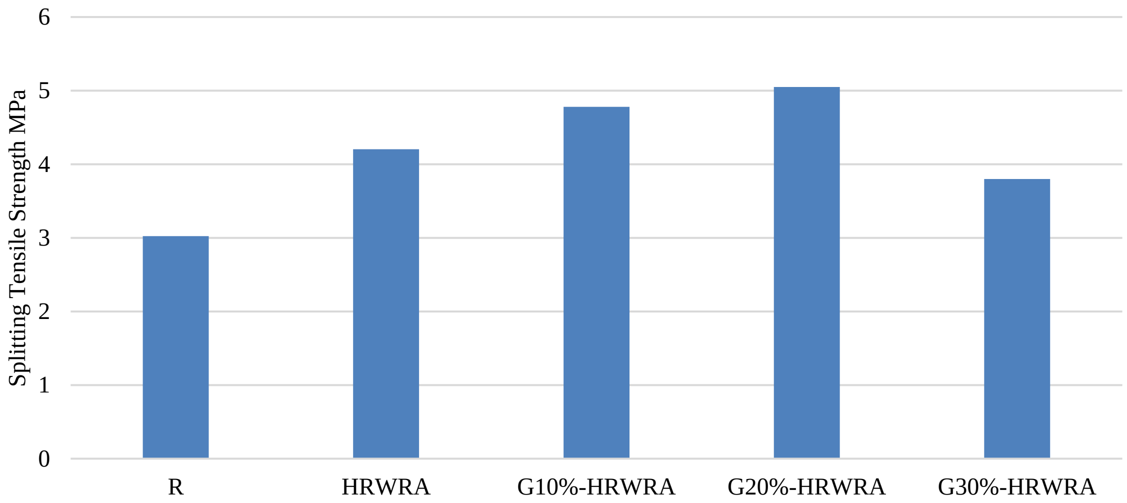


Fig. 7. The splitting tensile strength for the concrete specimens

4.3 Dynamic Modulus of Elasticity

The results of the dynamic modulus of elasticity (EcD) test also show that the HRWRA and finely ground green glass powder have a strong effect on the stiffness and internal strength of concrete. The test was conducted using cylindrical specimens (100 × 200 mm) and was based on the lowest resonant frequency using ASTM C215 (2014) [34, 35] according to Fig. 8. The reference mixture (R) had a dynamic modulus of 35.9 GPa and the addition of 1% HRWRA resulted in a modulus of 37.1 GPa which was an improvement of 3.34%. This improvement is due to better particle dispersion, lower internal porosity and denser cementitious matrix that are created by the effect of the superplasticizer.

Fig. 8. The dynamic modulus of elasticity test

Better results were found when green glass powder was added. The dynamic modulus values of the mixtures G10%-HRWRA and G20%-HRWRA were 38.9 GPa and 41.0 GPa, respectively, which were 8.36% and 14.21% higher than the reference mixture. It can be concluded that the G20%-HRWRA mixture gave the best performance which suggests that a replacement level of 20% is optimum in terms of the pozzolanic reaction and the micro-filler effect. As more C-S-H gel forms, pores are refined, resulting in a denser microstructure and higher stiffness, and thereby higher efficiency of stress-wave propagation through the concrete.

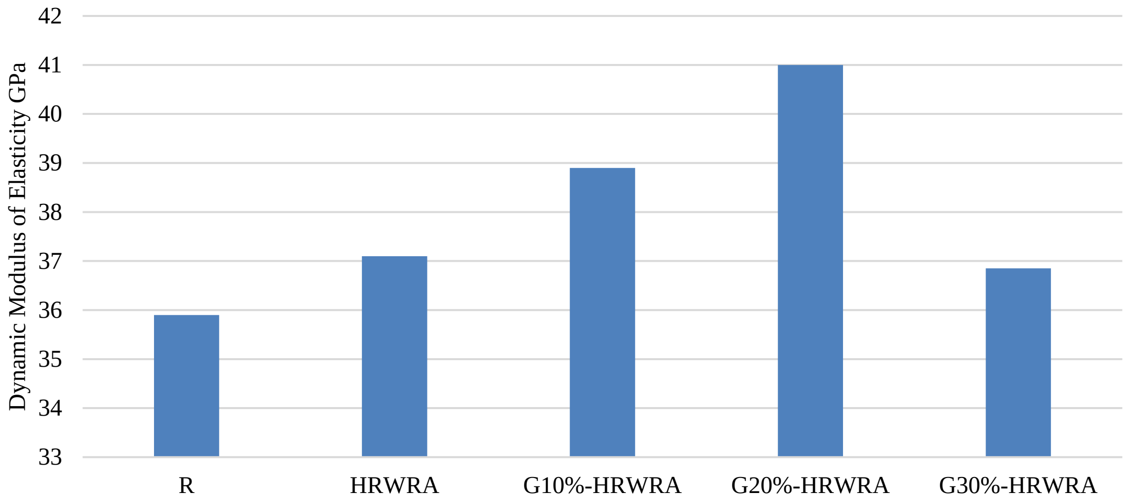


Fig. 9. The dynamic modulus of elasticity for the concrete specimens

When the replacement level was raised to 30%, the dynamic modulus was lowered to 36.85 GPa, which is 2.65% more than the reference mixture. This is about 10.1% less than the G20%-HRWRA mixture, which means that too much glass powder is not favorable, as it will deplete the available cement for hydration. This means that the good pozzolanic and micro-filler properties are not fully compensated for by the dilution effect, so that the stiffness is reduced. In conclusion, the dynamic modulus (41.0 GPa) of the 20% G20%-HRWRA mixture is the highest, and the 20% G20%-HRWRA mixture gives the best combination of stiffness, microstructural refinement and sustainability among all mixtures, as seen in Fig. 9.

4.4 Sustainability Assessment

The developed concrete mixes were assessed in terms of their sustainability as expressed by minimizing the use of cement and its environmental impact. When Portland cement is partially substituted with green glass powder, the CO_2 emissions in concrete production are reduced directly. Portland cement is the main source of CO_2 in concrete production, and so that's why using green glass powder helps to reduce CO_2 emissions directly. For this study, the CO_2 emission was assumed to be 0.9 kg CO_2 per kg of Portland cement, depending on the manufacturers data sheet. Using the same approach, the estimated CO_2/m^3 emission for the reference mixture of Portland cement (550 kg/m^3) was 495 kg CO_2/m^3, while that for the G20%-HRWRA mixture of Portland cement (440 kg/m^3) was approximately 396 kg CO_2/m^3, which corresponds to a reduction of approximately 99 kg CO_2/m^3.

Table 8. The sustainability indicators of the reference concrete and G20%-HRWRA concrete

Mixture	OPC kg/m^3	Estimated CO_2 kg/m^3	Carbon Intensity kg CO_2/MPa	Eco-efficiency MPa/kg CO_2
R	550	495	11.12	0.0899
G20%-HRWRA	440	396	6.83	0.1465

In order to evaluate the sustainability further, the carbon intensity was calculated by dividing the estimated CO_2 emission with the compressive strength obtained, and the eco-efficiency index was calculated by dividing the compressive strength with the CO_2 emission involved. The carbon intensity for the reference mixture was 11.12 kg CO_2/MPa while for G20%-HRWRA mixture, it was 6.83 kg CO_2/MPa which is around 38.6% lower. Likewise, the eco-efficiency was enhanced from 0.0899 MPa/kg CO_2 to 0.1465 MPa/kg CO_2, which is about 62.9%, as shown in Table 8. The overall findings are consistent, showing that green glass powder can be a practical and eco-friendly substitute for Portland cement, as it can help to lower the use of cement and its CO_2 emissions.

4.5 Scanning Electron Microscopic

The discussion of the microstructural properties of the best G20%-HRWRA mix versus the R is given with specific references to the cementitious matrix and ITZ. The purpose of this comparison is to point out the major mechanisms that have caused the performance improvement.

4.5.1 Scanning Electron Microscopic of Concrete Matrix

The scanning electron microscopic images of the cementitious mixtures have indicated that the G20%-HRWRA mix is highly microstructurally refined in comparison to the R as shown in Fig. 10 and Fig. 11. The matrix is quite heterogeneous and loosely packed in the R, showing the discontinuity of hydration products distribution, a presence of visible capillary voids, and partially hydrated cement particles. The C-S-H gel appears in poorly interconnected state, but with clear crystalline phases like plate-like calcium hydroxide (C-H) and needle-like ettringite, meaning that the matrix has not been fully densified. This structure means that its porosity and internal cohesion are relatively higher and less favorable to transferring the stress and crack resistance.

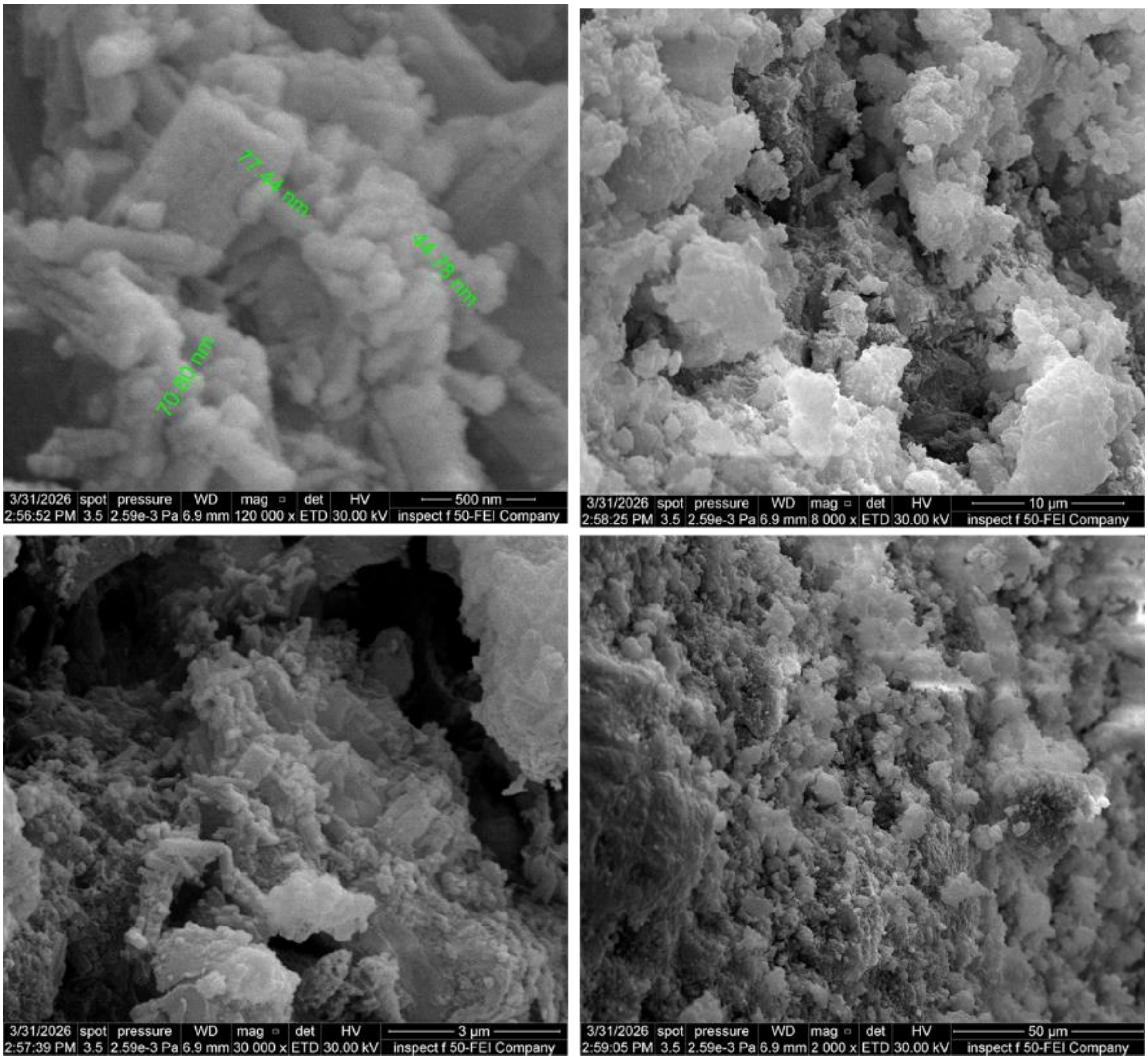


Fig. 10. SEM images for the concrete matrix of R mixture

As it could be observed in Fig. 10, the microstructure of R indicates an uneven packing system with prominent micro-defects and discontinuities in the hydration products. On the other hand, the case to the G20%-HRWRA mix, the matrix is much denser and also higher regularity, as demonstrated in Fig. 11, where the hydration items form a continuous and compact network. In the C-S-H gel, fewer crystals of calcium hydroxide (C-H) are evident, and the C-S-H gel is more uniform and abundant than in the reference mixture. The results also agree with this interpretation, showing a decrease in the Portlandite peak areas and an increase in the amorphous phase, suggesting a pozzolanic reaction. The finely grounded green glass powder, less than 45 µm, does so in two complimentary ways. Firstly, the amorphous silica reacts with calcium hydroxide to form more secondary C-S-H gel which consumes the Portlandite and raises the amount of solid hydration products. Secondly, it enhances the particle packing as filling effect of micro-filler which reduces capillary porosity, thus yielding a dense cementitious matrix. The SEM observations further revealed that the interfacial transition zone of the G20%-HRWRA mixture is more compact and contains less microcracks while the bonding between the cement paste and aggregate is better. The results of the SEM and XRD indicate that combined with the optimized ITZ, the improved matrix in the G20%-HRWRA mixture gives rise to the observed increase in the compressive strength, splitting tensile strength and dynamic modulus of elasticity. Previous studies report similar results: highest levels of replacement finely ground glass powder led to better microstructural refinement and mechanical characteristics [31]. Finally, the SEM images showed no clear presence of $Ca(OH)_2$ and (CH) in the mixes with glass powder, indicating effective pozzolanic activity, whereas the reference mix.

4.5.2 Scanning Electron Microscopic of ITZ

Fig. 12 and Fig. 13 show that the SEM observations indicate that there is a significant change in the microstructural form of both the cementitious matrix and the interfacial transition zone (ITZ) with the addition of the finely ground green waste glass powder. The hydration is relative and loosely packed into a matrix that looks relatively heterogeneous in R, with hydration products distributed discontinuously, capillary voids evident and a portion of partially hydrated cement in the sample. C-S-H gel is loosely connected, whereas separate crystal faces like plate-like calcium hydroxide (CH) and needle-like ettringite are also noticeable, which means that it did not densify fully. Likewise, the weak and porous structure of the ITZ in R is characterized with interfacial gaps, microcracks, high concentration of CH crystals, leading to poor bonding between the aggregate and the surrounding paste. Fig. 12 reveals that the morphology of both the matrix and ITZ is non-uniform and has high concentration of defects that enable crack initiation and propagation. Conversely, the G20%-HRWRA mixture has a very fine and densified microstructure of the matrix and ITZ, which is evident in Fig. 13.

A close and continuous C–S–H gel network dominated the matrix and reduced CH crystals significantly, which is the indication of the success of the pozzolanic reaction. Green glass powder (passing 45 µm) inclusion is involved in this improvement in a twofold process. To begin with, its large proportion of amorphous silica is actively reactive with calcium hydroxide to form more secondary C–S-H gel that increases the solid portion and minimizes weak crystalline products. Second, it has an ultra-fine particle size which gives it a strong micro-filler effect that enhances the packing of particles, filling of micro voids and decreased capillary porosity. It leads to a more homogeneous and highly bonded matrix having better structural integrity. More to the point, the use of green glass powder is especially efficient in the ITZ, which is usually the weakest area in concrete.

The small particles of glass powder will be concentrated at the interface more than the others because of their size and mobility, and this will result in localized densification of this crucial area. This effect causes a thinness of the ITZ, a minimal porosity and an increase in continuity between the aggregate and the cement paste. Moreover, excess CH is replaced by a solid C–S–H layer owing to the pozzolanic reaction in the ITZ, thus, converting the interface of a weak transition zone to a mechanically integrated zone. At varied magnification, G20%-HRWRA ITZ is compact where there is minimum microcracking and adhesive which means that there is enhanced stress transfer across the interface and less stress concentration area. This hybridization of both the matrix and ITZ shows the best balance between the hydration and the pozzolanic activity at the 20 percent replacement level where the positive impact of the glass powder with 1 % of HRWRA is maximized without affecting the binder system.

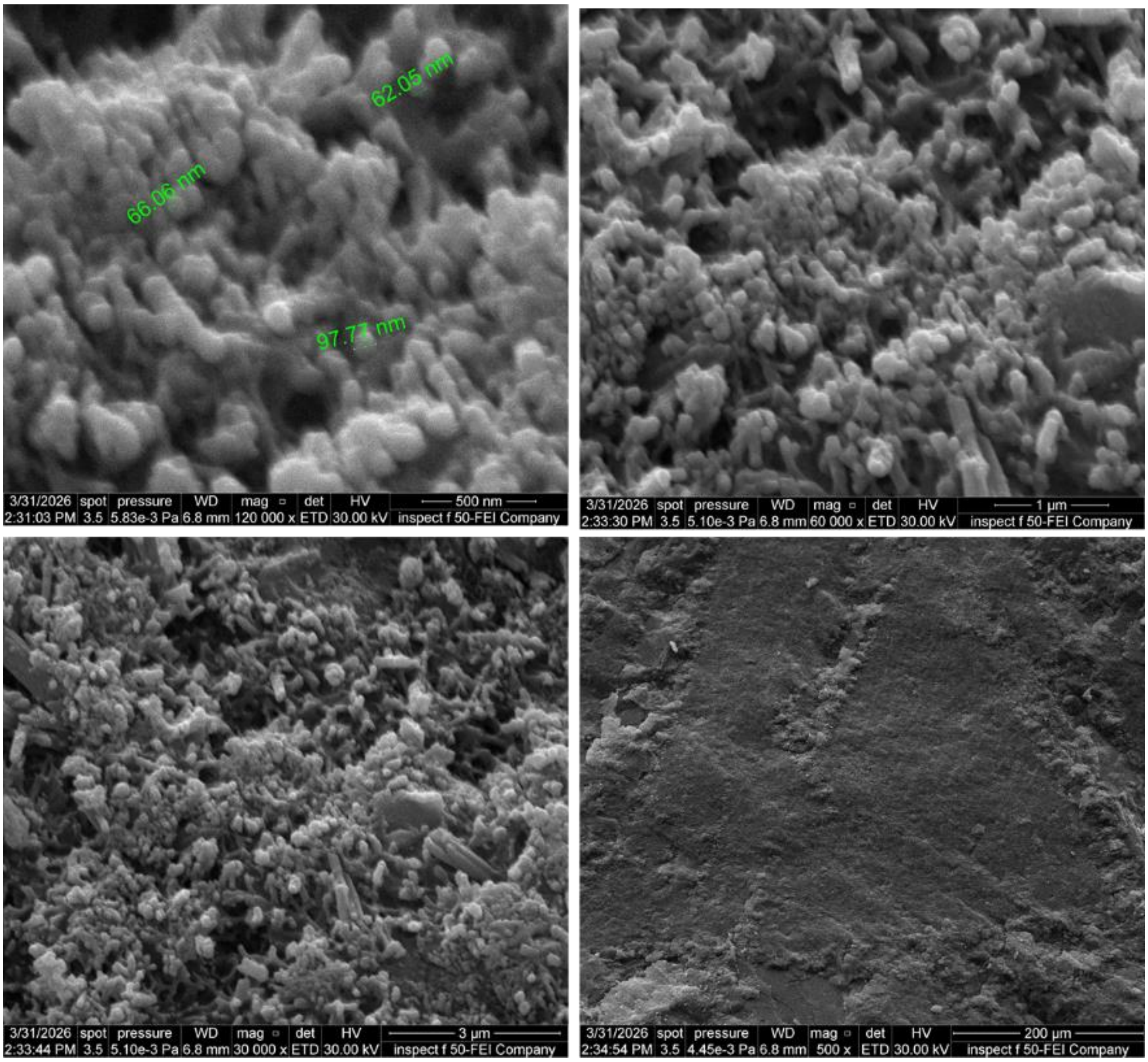
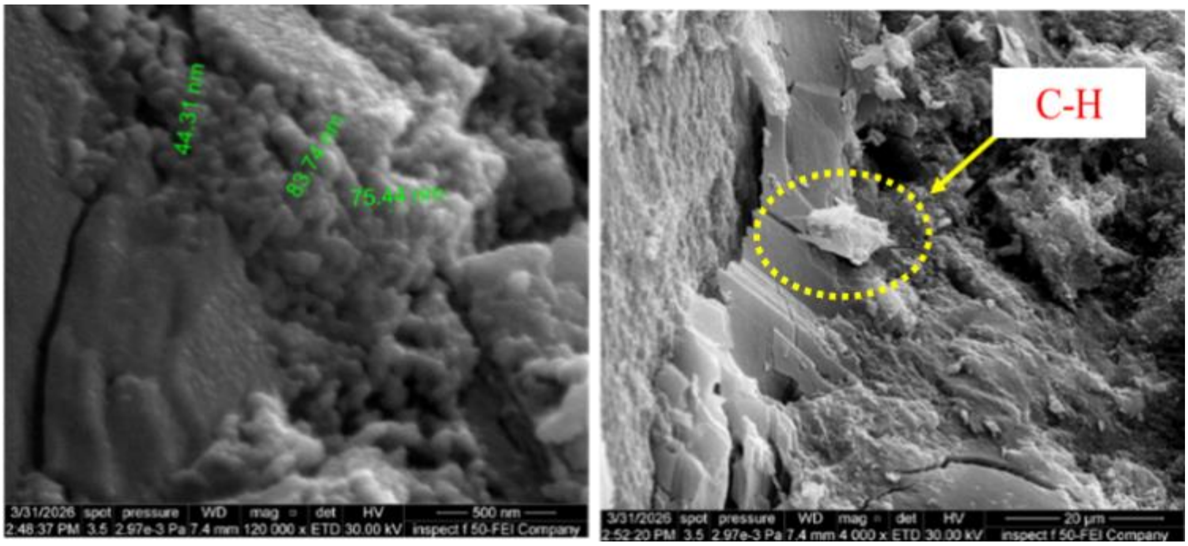


Fig. 11. SEM images for the concrete matrix of G20%-HRWRA mixture



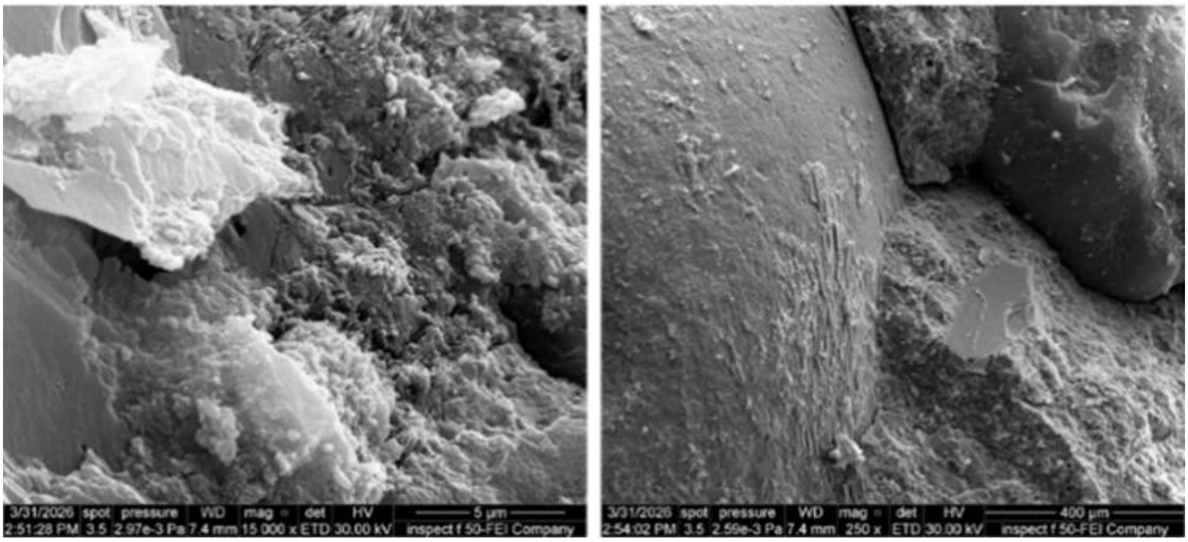


Fig. 12. SEM images for the ITZ of R mixture

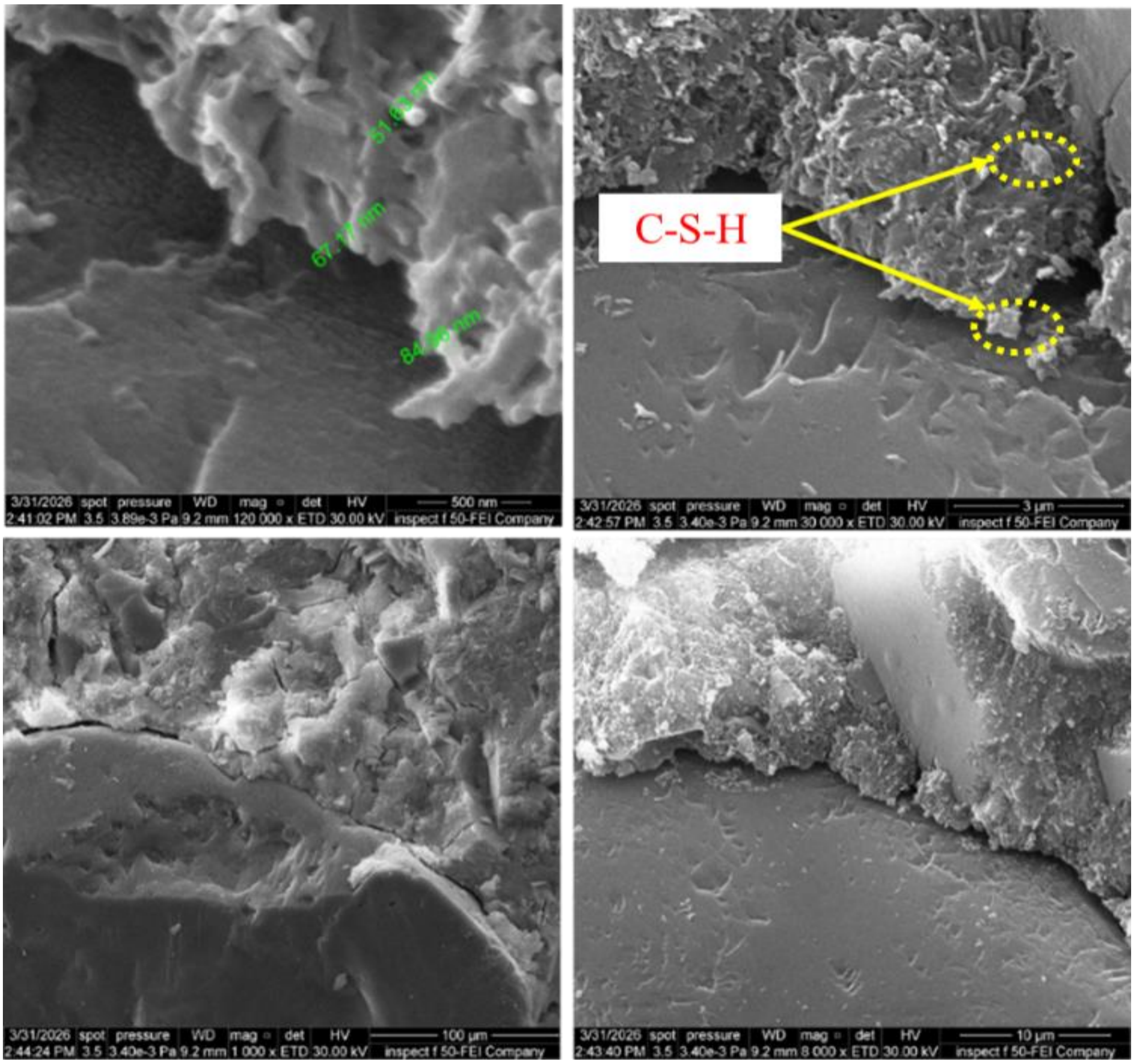


Fig. 13. SEM images for the ITZ of G20%-HRWRA mixture

These microstructural characteristics are entirely in line with the shown mechanical performance improvement in the compressive strength, splitting tensile strength and dynamic modulus of elasticity, which confirms that densification of the matrix and the ITZ is the determining factor of the mechanical performance of the developed concrete. Recent studies have shown similar results in which finely ground glass powder exhibited a high level of microstructural integrity and interfacial bonding with an optimum level of replacement. Finally, the ITZ of the glass powder mix showed a limited distinguishable presence of CH, whereas CH was clearly and abundantly observed in the ITZ of the reference mix, indicating improved interfacial densification.

4.6 X-Ray Diffraction Analysis

The XRD patterns of the reference concrete (R) and G20%-HRWRA are shown in Figs. 14 and 15, respectively. The diffraction peaks of both mixtures are characteristic of the hydrated cementitious materials, but there are distinct variations in intensity and distribution of the major phases. G20%-HRWRA contains a wider amorphous hump between 15–35° (2θ) compared with the reference mixture, which suggests that there are more amorphous hydration products, mainly calcium silicate hydrate (C-S-H) gel.

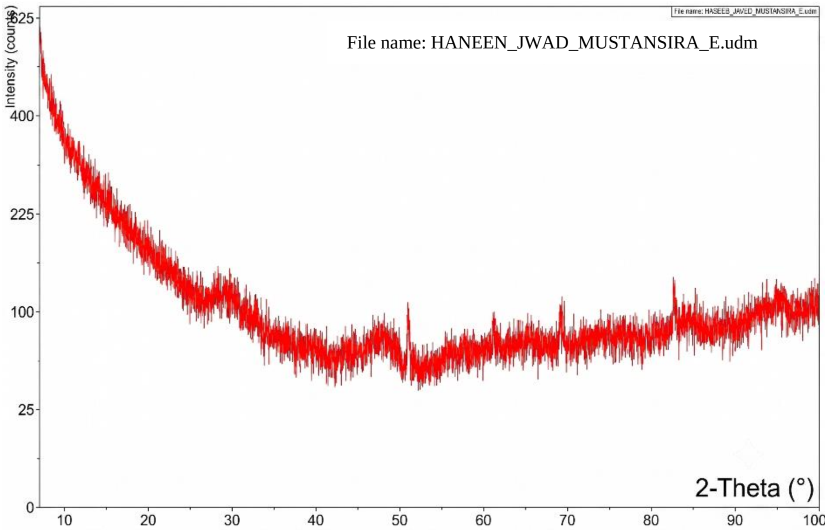


Fig. 14. XRD pattern of the reference mixture

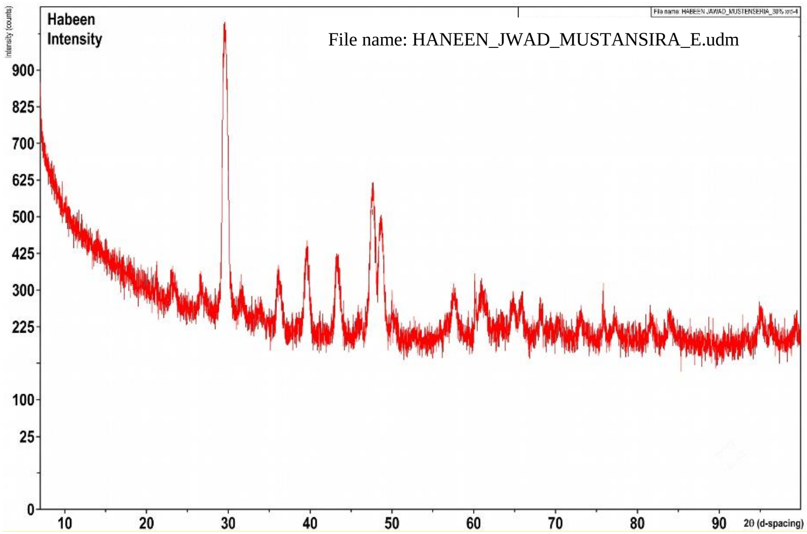


Fig. 15 XRD pattern of the 20%G-HRWRA mixture

The pozzolanic reaction of the finely ground green glass powder seems to have led to formation of extra secondary C-S-H. The diffraction peak of quartz (SiO_2) was also observed in the G20%-HRWRA mixture with a pronounced peak at about 26.7° (2θ). The increased intensity of this peak is believed to be due to the extra silica that was added to the concrete mixture with the green glass powder. The biggest difference between the two mixtures is correlated to the Portlandite [$Ca(OH)_2$] peaks that appear at around 18°, 34°, and 47° (2θ). These peaks show greater intensity in the reference concrete than in G20%-HRWRA. This relative reduction means the calcium hydroxide consumed in the pozzolanic reaction, in which the amorphous silica in the green glass powder reacts with Portlandite to form further C-S-H gel. Therefore, G20%-HRWRA mixture has a more compact hydration structure and a finer cementitious matrix. Overall, Comparative XRD analysis shows that the addition of green glass powder improves hydration process by decreasing Portlandite amount and increasing hydration products. These results are also in line with SEM observation results and further demonstrate the better microstructure, mechanical properties and durability of the mixture with G20%-HRWRA.

5. Conclusion

From the results of this study, the following conclusions can be drawn:

- The use of superplasticizer and green waste glass powder as a partial cement replacement showed a significant improvement of the mechanical performance of concrete, and proved that high-performance sustainable concrete was possible.
- The compressive strength results indicated that there was an unquestionable rising trend up to 20 % replacement after which the G20%-HRWRA mix attained the highest strength of 58 MPa and this amounts to an increment of some 30.3 % of the reference mix (R).
- The tensile strength had increased by 67 % to the highest tensile strength of 5.05 MPa in the G20%-HRWRA.
- Dynamic modulus of elasticity was also on the same trend with the highest value of G20%-HRWRA being 41 GPa which corresponds to a 14.2 % increase over the reference mix, which indicates greater stiffness and structural integrity.
- SEM analysis proved that strong evidence of the mechanical results was obtained in that the G20%-HRWRA mix had a densified cementitious matrix with a dominant and well developed C-S-H gel structure and a significant decrease in the number of calcium hydroxide (CH) crystals.
- ITZ in G20%-HRWRA demonstrated a high level of refinement, reduced porosity, reduced microcracks, and improved bonding of cement paste to the aggregate making it an integrated structural zone.
- The replacement of cement by 20 % green waste glass powder with 1 % of HRWRA can be considered a sustainable and effective method of reducing cement consumption and environmental cost, and at the same time, improving mechanical and microstructural properties of concrete.
- This enhancement of the performance can be explained by synergy of the pozzolanic reaction and micro-filler effect of the finely ground glass powder, which increased the density of the packing of the particles and minimized the capillary porosity of the cementitious matrix.
- The findings demonstrate that there is a high level of correlation between microstructural refinement and mechanical performance which proves that the further enhancement of the quality of matrix densification and ITZ quality directly control the behavior of the produced concrete.
- The G20%-HRWRA mixture was found to have considerable environmental advantages which can be seen in the reduced estimated CO_2 emissions of about 99 kg/m^3, carbon intensity index of 38.6% and the increased eco-efficiency by 62.9% compared to the reference mixture.

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