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Evaluating high performance concrete properties partially replacing waste glass powder WGP and waste high density polyethylene (HDPE) beads

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ABSTRACT

The abundant availability of High-Density Polyethylene (HDPE) and Waste Glass Powder (WGP) results from their large-scale production and single-use policies. Numerous methods have been explored by researchers to incorporate these waste materials as alternatives for concrete components. This research aims to investigate the synergistic effect that arises from combining these two waste materials in concrete. The study involved experimental investigations using WGP as cement substitutes in concentrations of 5%, 10%, 15%, and 20% and HDPE as fine aggregate substitutes in concentrations of 5%, 10%, 15%, and 20%. Additionally, different blends were created by combining WGP and HDPE. Various properties, including compressive, flexural, tensile strength slump, density, and water absorption were thoroughly analyzed. The scope of the microstructural investigation was expanded by the use of energy-dispersive X-ray (EDX), X-ray diffraction (XRD), and scanning electron microscopy (SEM) techniques. Results demonstrated that the highest strength value, with a remarkable 13.6% increase compared to the control mix, was achieved with a combination of 10% WGP and 5% HDPE. Based on these findings, the simultaneous replacement of WGP and HDPE can be regarded as a promising approach in concrete applications.

Keywords: WGP, HDPE, Waste materials, High performance concrete

1. INTRODUCTION

The construction industry faces increasing pressure to employ sustainable alternatives in the manufacture of concrete due to the increasing demand for construction materials. Because of the significant carbon dioxide (CO2) emissions and environmental effects of cement production, it is critical to achieving a balance between cost and environmental friendliness (Hwang et al., 2014; Daniel et al., 2020; Nidheesh and Kumar, 2019; Pedro et al., 2020; Vijayalakshmi et al., 2013). Cementitious materials are an increasing focus of research because they can reduce greenhouse gas emissions without sacrificing the required qualities of concrete (Latawiec et al., 2018; Louise and Frank, 2013; Rui et al., 2020; Akbar and Liew, 2020; Liew and Akbar, 2020).

Research on the use of waste glass powder (WGP) and recycled fragments of glass in concrete has increased recently in response to environmental concerns (Ahmad et al., 2024; Yan et al., 2024; Singh and Mohanty, 2024; Belkadi et al., 2024). In particular, WGP and HDPE have attracted attention as an alternative replacement for some of the sand and cement in concrete blends (Hossam et al., 2019; Ahmad et al., 2025; Sadiqul et al., 2017; Han et al., 2024; Flores et al., 2024; Al-Mashhadani et al., 2024). Introducing WGP as a partial substitute for cement in mortar and concrete appears to be a significant step in environmentally conscious construction practices (Biplob et al., 2015).

Additionally, WGP-incorporated concrete has demonstrated improved compressive strength and internal microstructure (Zhi-hai et al., 2019; Aliabdo et al., 2016). Because advancing sustainability and environmental protection is urgently needed, it is imperative that these goals be incorporated into construction procedures. Reportedly, the building and construction sectors accounted for 36% of total energy consumption and 39% of energy-related carbon dioxide (CO2) emissions in 2018. The manufacture of building materials, such as steel, cement, and glass, was the source of 11% of these emissions. Cement production constituted 5% of industrial energy and 3% of global energy consumption among diverse energy-intensive sectors. Moreover, it released 0.9 tons of CO2 for every ton of cement produced.

These statistics illustrate how important it is to address the negative environmental effects of cement production as well as its larger implications for energy consumption and greenhouse gas emissions. The dedication to sustainable building methods is fueling a growing interest in the construction industry for waste or recycled materials to be added to concrete. Glass garbage from local small businesses and their environs currently ends up in landfills. Glass, on the other hand, is an inert material that can be recycled and used again without going through chemical changes (Aimin and Shayam, 2004). Waste glass can be crushed to particular sizes and used as aggregate in a variety of applications, such as water filtering, grit plastering, sports turf covering, and as a sand alternative in concrete mixtures, in addition to its conventional use as a cullet in the glass manufacturing process (Carpenter and Cramer, 1999).

This approach not only helps reduce waste and landfill burden but also promotes the sustainable use of resources in construction-related activities. High-density polyethylene (HDPE) is a well-known ethylene polymer that finds extensive use in many daily applications due to its exceptional strength-to-density ratio. HDPE polymer resins decrease plastic and drying shrinkage cracking by reducing permeability when added to concrete. The superior post-crack strength of polymer-reinforced concrete keeps the structure from failing right away. Depending on the kind of HDPE material and design mix chosen, different HDPE-reinforced concrete has different particular properties. Waste glass powder (WGP) improves the compressive strength of concrete by enhancing its internal microstructure (Aliabdo et al., 2016).

The inclusion of recycled glass cullets and recycled fine aggregate in cement mortar also significantly boosts strength and durability (Jian-Xin et al., 2020). Noteworthy improvements in compressive strength, split tensile strength, and flexural strength are observed when WGP and granular steel slag replace cement and fine aggregate in concrete (Shahir et al., 2018; Xin et al., 2016). Moreover, utilizing glass powder and rubber waste as replacements for sand and cement simultaneously improves concrete workability. High-density polyethylene (HDPE) can effectively replace fine aggregate in concrete, further improving these properties. The combined usage of HDPE as a fine aggregate substitute and WGP as a cement substitute, however, is not well covered by current research.

The simultaneous inclusion of plastic waste and waste glass powder as a replacement material for fine aggregate and cement enhanced the workability of concrete. Investigations showed an improvement in strength when 10% of WGP and 5% HDPE were added to concrete. The present research works have shown little information on the combined use of HDPE as a replacement for fine aggregate and WGP as a replacement for cement. therefore, this study was directed towards the combined use of HDPE and WGP in the concrete under various proportions. The scope of the present study is focused on the strength, microstructure behavior, and environmental impact by using waste products in concrete to reduce global warming. In addition, future studies on long-term results have been suggested to find out different long-term reactions.

2. MATERIALS AND METHOD

Local sources provided all of the materials used in the present investigation. According to ASTM C114-85 standards, a chemical analysis of the cement for investigation—typical Portland cement—was performed. The fine aggregate was composed of organically formed desert sand that met ASTM C136-84 grading requirements, with a maximum size of 4.75 mm and a bulk density of 1561 kg/m3. With a maximum size of 20 mm and a bulk density of 1618 kg/m3, the coarse aggregate was supplied by a nearby company.

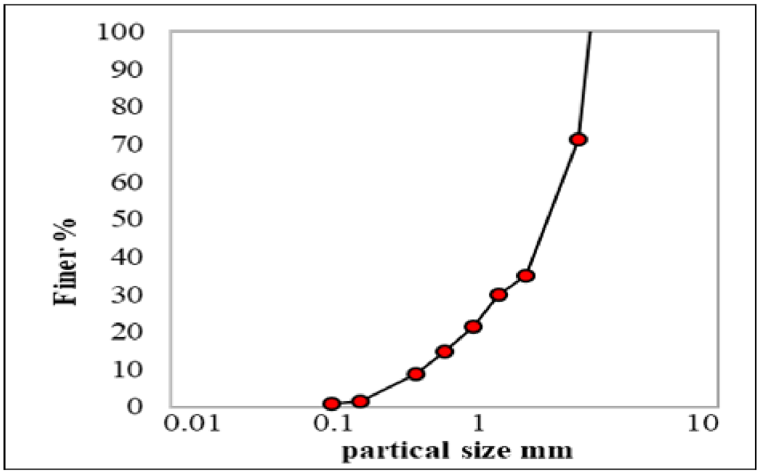
As an alternative to cement, crushed waste glass was utilized as displayed in Figure 1 its physical properties, such as sieve analysis and particle size, were reviewed. As shown in Figure 3 among the containers that were collected as waste glass were bottles, jars, and flat glass. Furthermore, as illustrated in Figure 2 Fizlestari Plastic Company's High-Density Polyethylene (Black HDPE Recycled Pellets) with a density of 595 kg/m3 and a maximum size of 3.6 mm was applied. Table 1, presents the high-performance concrete tests and the percentages of the waste materials and control mix design presented in (Table 2 and 3).

Figure 1 a) Waste Glass Powder b) HDPE Beads

Figure 2 HDPE beads size

Table 1 Tests Details

No.	Test	Specimen Shape	Size mm	Specification	Reference
1	Slump	Cone	200x100x300	ASTM C143	(ASTM C143/C143 M-20)
2	Compressive Strength	Cube	100x100x100	ASTM C39	(ASTM C39/C39M-20)
3	Flexural Strength	Prism	100x100x400	ASTM C293	(ASTM C293/C293 M-16)
4	Split Tensile Strength	Cylinder	100x200	ASTM C496	(ASTM C496-11)
6	Water Absorption	Cube	100x100x100	ASTM C642	(ASTM C 642-13)



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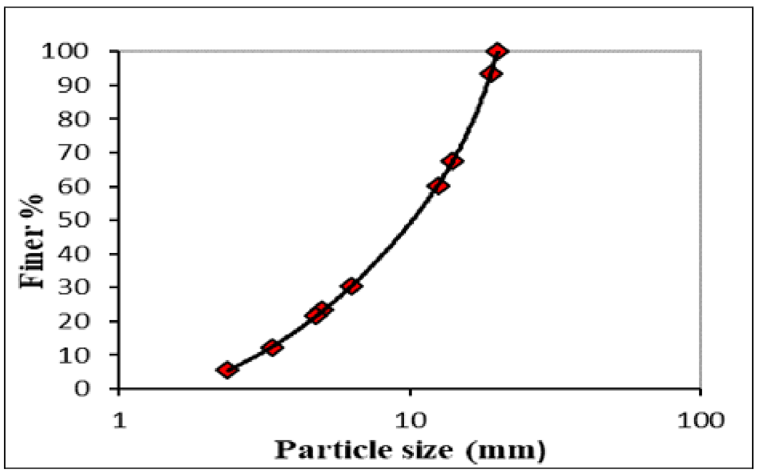

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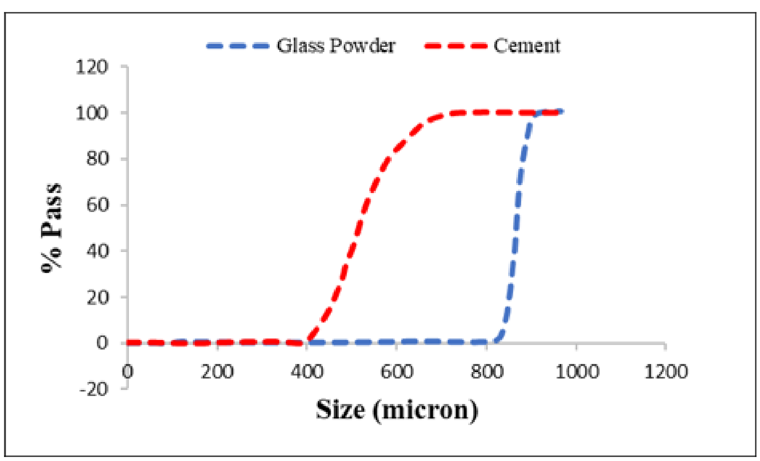


(c)

Figure 3 Particle size analysis of (a) sand (b) coarse aggregate (c) cement and waste glass powder

Table 2 Preparation of Specimen

No.	Specimens Code	Content of WGP replaced as cement (%)	Content of waste HDPE replaced as sand (%)
1	Control	0%	0%
2	S1 – S4	0%	5% - 10% - 15% - 20%
3	S5 – S8	5% - 10% - 15% - 20%	0%
4	S9 – S12	5% - 10% - 15% - 20%	5%
5	S9 – S12	5% - 10% - 15% - 20%	5%
6	S13 – S16	5% - 10% - 15% - 20%	10%
7	S17 – S20	5% - 10% - 15% - 20%	15%

Table 3 The control mix design

w/c ratio	Superplasticizer %	Cement Kg	Fine aggregate Kg	Coarse aggregate Kg
0.30	1.5 %	1	1	2

The purpose of choosing particular replacement percentages for waste glass powder (WGP) and high-density polyethylene (HDPE) in concrete is to achieve the optimal balance between material performance, cost-effectiveness, and environmental benefits. Each percentage was chosen based on a systematic evaluation of the following factors:

Material Properties and Compatibility: Waste Glass Powder (WGP) improves the cement matrix due to pozzolanic properties, while excessive levels may decrease strength due to brittleness or incomplete hydration. High-density polyethylene (HDPE) impacts density and porosity, with excessive use reducing strength due to poor bonding and hydrophobicity.

Performance Optimization: Concrete performs better when substituting 10% WGP and 5% HDPE. HDPE reduces weight without significantly compromising strength, while WGP improves pozzolanic processes and fills micro-voids.

Environmental Impact: Using 10% WGP and 5% HDPE promotes sustainability by recycling waste, reducing reliance on natural resources, and decreasing carbon emissions, all while maintaining concrete quality.

Economic Considerations: These replacement sections are affordable, minimizing reliance on costly traditional materials and avoiding additional processing expenses, therefore being appropriate for large-scale applications.

3. RESULTS AND DISCUSSION

The discussion in this section starts with an examination of the granulometry investigations of the raw materials utilized in concrete production. Evaluating the filler effect of waste glass powder and black high-density polyethylene on concrete packing performance is crucial. Subsequently, by correlating the 28-day peak compressive strength replacement with waste glass powder and high-density polyethylene, we can elucidate their roles in the bonding mechanism of optimized concrete. Additionally, various tests including flexural, splitting, slump, density, and water absorption were conducted to assess their implications. Chemical compound detection of raw materials was carried out using Wavelength Dispersive X-ray Fluorescence (WDXRF), XRD, SEM, and EDX analysis.

Cube Compressive Strength

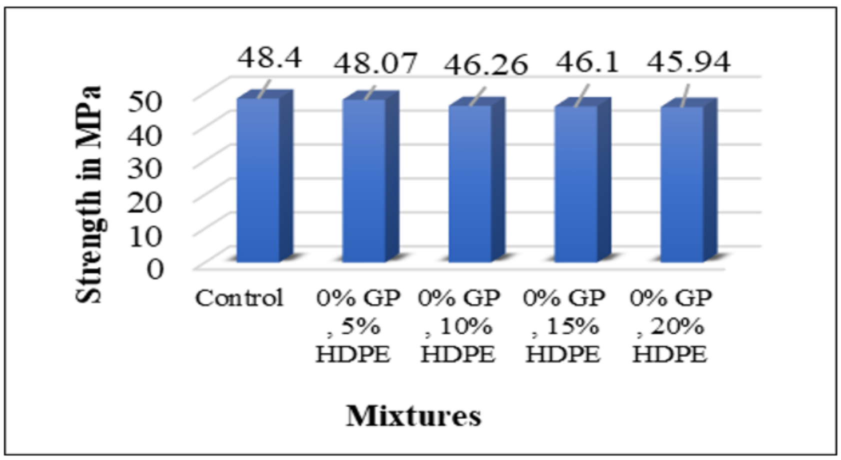
The results for compressive strength, as illustrated in Figure 4 demonstrated that the control mixture exhibited a strength of 48.4 MPa. Samples S1–S4, with 5%–20% HDPE substituted, showed reduced compressive strength. The percentage decrease ranged from 0.6% to 5% as the HDPE percentage increase compared to the control mix. Conversely, samples S5–S8, substitute with 5%–20% WGP, exhibited an enhancement in cube compressive strength for 5%, 10%, and 15% replacements, with the strength increase ranging between 1.75% and 7% compared to the control mix (Islam et al., 2017; Al-Mashhadani et al., 2023). Samples S9–S12, which were replaced with a combination of 5%–20% WGP and 5% HDPE, demonstrated the highest strength when 10% WGP and 5% HDPE were used, resulting in a 13.6% increase compared to the control blend.

However, when samples S13–S24, replaced with a combination of WGP and HDPE, were tested, compressive strength was reduced. The percentage reductions ranged from 1.5% to 15.4% compared to the normal mix. The sample with the highest cube-crushing strength was S10, which contained 10% WGP and 5% HDPE. The sample with the lowest strength, S11, which contained 20% WGP and

5% HDPE, had a cube crushing strength of 40.69 MPa. Additionally, S9, which included 5% WGP and 5% HDPE, showed a 46.64 MPa compressive strength, while S24, which included 20% WGP and 20% HDPE, showed a 43 MPa compressive strength. The large surface area of the fine glass particles is responsible for the strength increase, as was previously mentioned.

In contrast, higher HDPE levels were linked to decreased strength because they caused inadequate hydration (Yu et al., 2016). Notably, the results highlight that the combination of 10% WGP with 5% HDPE can significantly enhance and increase strength performance by up to 13.6% compared to the control blend, owing to the strong attractive forces between the polymer molecules and their hardening HDPE. Larger surface areas of fine glass particles may be the cause of combination mixtures' increased strength. Increased HDPE proportions caused inadequate hydration, which lowers strength.

This is why there was a fall in strength. Compared to the control mix, the compressive strength of the optimized mixtures with various proportions of waste glass powder and black high-density polyethylene was greater, as shown in (Figure 5). The hydrophobic nature of high HDPE in concrete can hinder hydration by reducing the availability of water and preventing the formation of calcium silicate hydrate (C-S-H), which is essential for strength development. To address this, surface modification of HDPE particles, the use of chemical additives like superplasticizers and accelerators, and optimized curing conditions can help enhance hydration.



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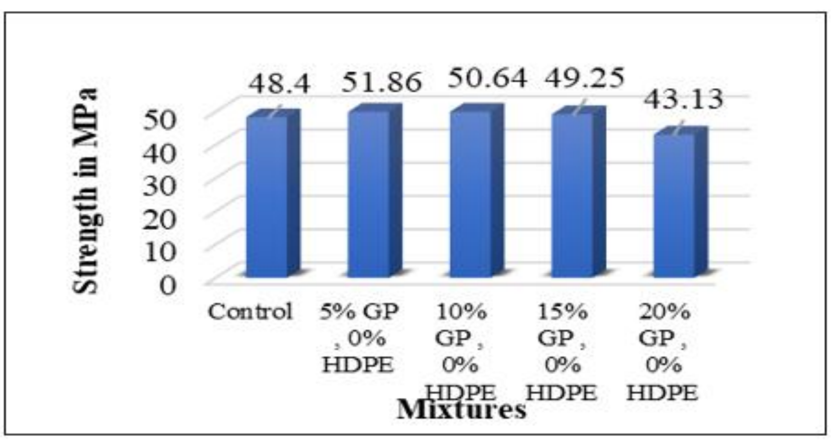

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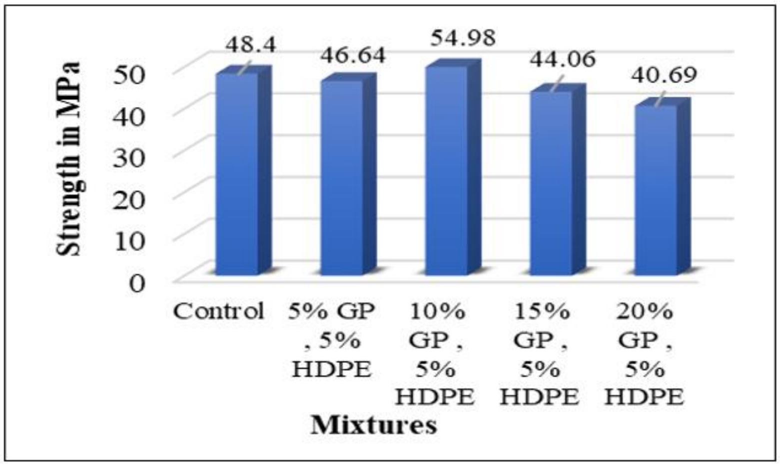
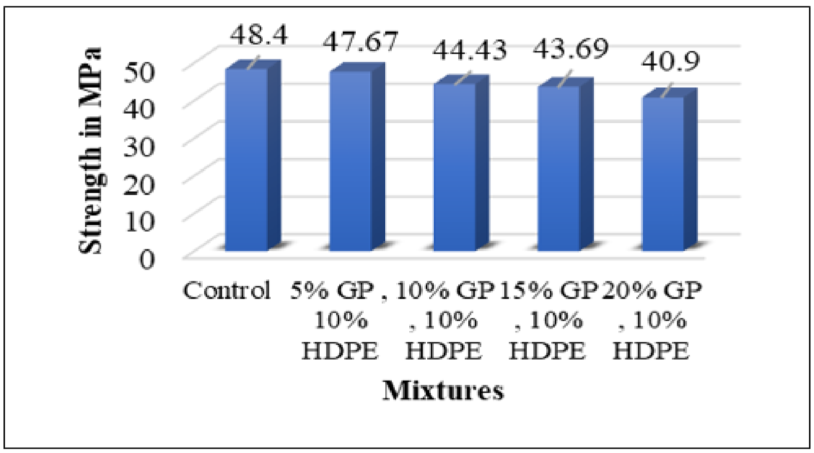
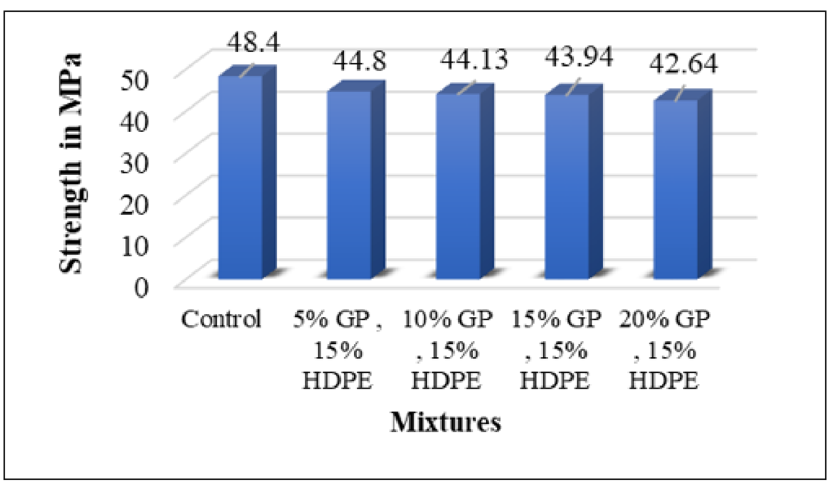

Strength in MPa
50
40
30
20
10
0
48.4
46.64
54.98
44.06
40.69
Control
5% GP , 5% HDPE
10% GP , 5% HDPE
15% GP , 5% HDPE
20% GP , 5% HDPE
Mixtures

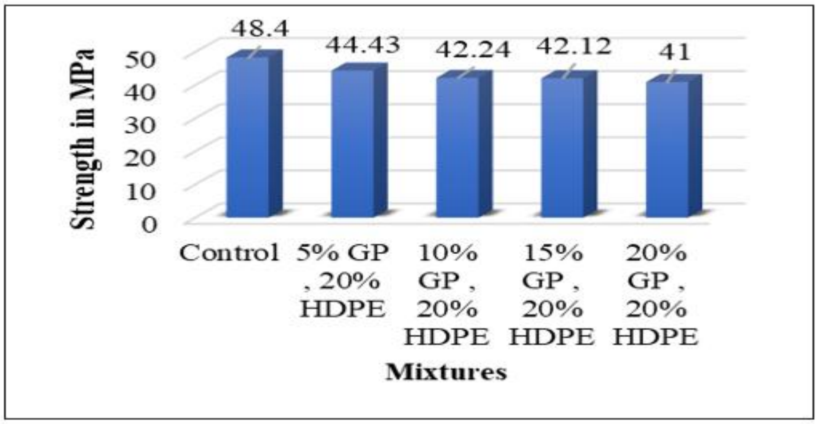
(c)


Strength in MPa
50
40
30
20
10
0
48.4
47.67
44.43
43.69
40.9
Control
5% GP , 10% HDPE
10% GP , 10% HDPE
15% GP , 10% HDPE
20% GP , 10% HDPE
Mixtures

(d)


Strength in MPa
50
40
30
20
10
0
48.4
44.8
44.13
43.94
42.64
Control
5% GP , 15% HDPE
10% GP , 15% HDPE
15% GP , 15% HDPE
20% GP , 15% HDPE
Mixtures

(e)



(f)

Figure 4 Results of the specimen's compressive strength, (a) 0-20% HDPE replaced, (b) 0-20% GP replaced, (c) 5% HDPE with 5-20% GP, (d) 10%HDPE with 5-20% GP, (e) 15%HDPE with 5-20% GP, (f) 20%HDPE with 5-20% GP

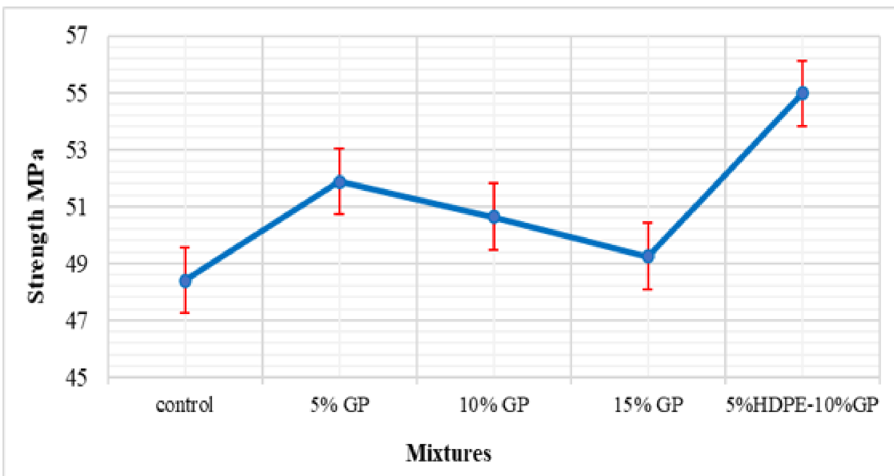


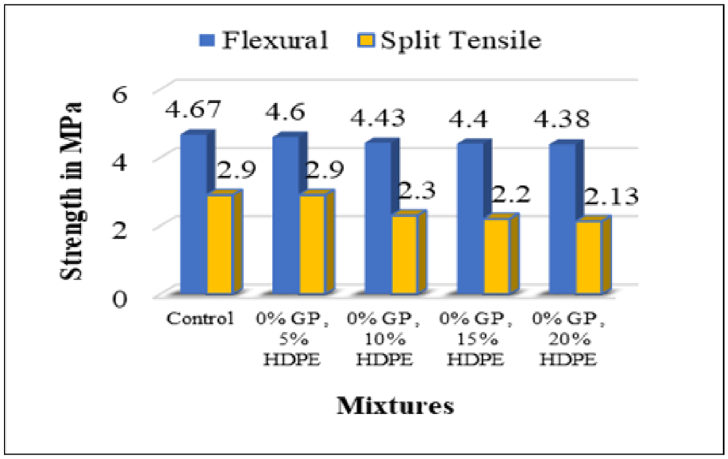
Figure 5 The compressive strength of the optimized mixtures compares to control

Flexural

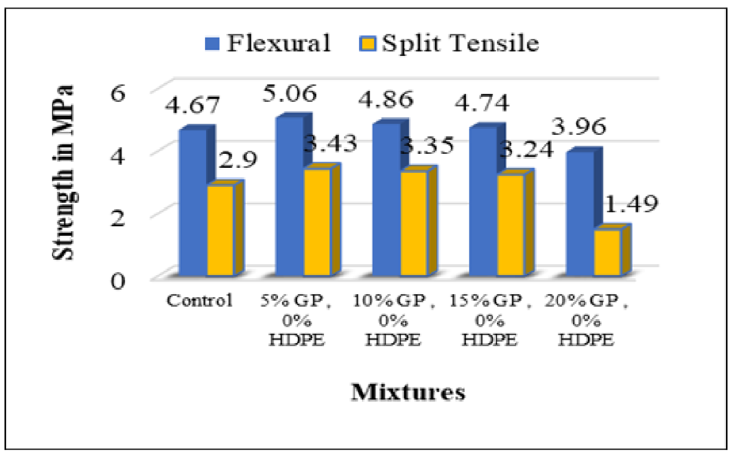
The results of the strength tests conducted at 28 days are displayed in (Figure 6). The flexural strength of the control mixture was found to be 4.67 MPa. Samples S1–S4, with 5% to 20% HDPE replacement, exhibited a gradual decrease in flexural strength, ranging from 1.5% to 6.2% compared to the control blend. Conversely, samples S5-S8, substituted with 5% to 20% WGP, displayed a high flexural strength, with the percentage increase ranging from 1.5% to 8.3% compared to the control blend. Samples S9 and S10, replaced with a combination of WGP and HDPE, demonstrated a 22% increase in flexural strength when 10% WGP and 5% HDPE were used, compared to the control blend.

However, when evaluating samples S11–S24, a slight reduction in flexural strength was eliminated, with percentage reductions ranging from 2.3% to 30% compared to the control blend. Among these samples, S8, which was replaced with 20% WGP, exhibited a flexural strength of 3.96 MPa, while S4, with a 20% HDPE replacement, showed a flexural strength of 4.38 MPa. Additionally, sample S9, using a combination of 5% WGP and 5% HDPE, demonstrated a flexural strength of 4.48 MPa, and sample S24, with the combination of 20% WGP and 20% HDPE, displayed a flexural strength of 3.94 MPa. Among the samples, S10 showcased the maximum flexural strength, while S12 demonstrated the minimum values compared to the normal blend.

The findings suggest that the inclusion of WGP and HDPE can influence the flexural strength of the concrete mixes, and careful selection of their combinations is crucial to achieving the desired flexural performance. Due to the Larger surface areas of fine glass particles may be the cause of combination mixtures' increased strength. Increased HDPE proportions caused inadequate hydration, which lowers strength. This is why there was a fall in strength (Sadiqul et al., 2017).



(a)



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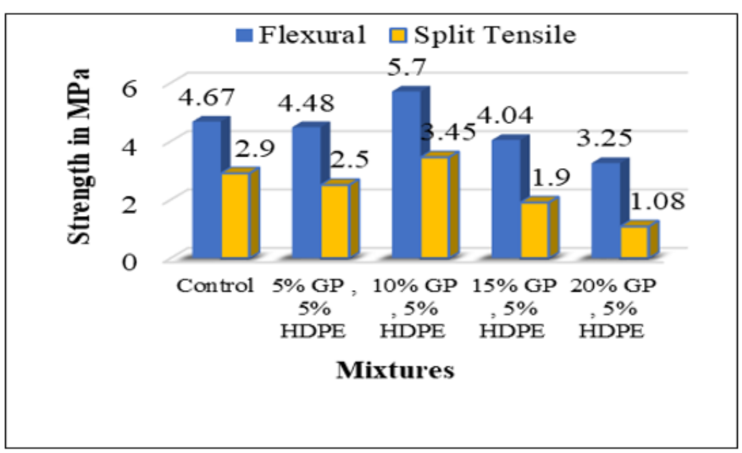

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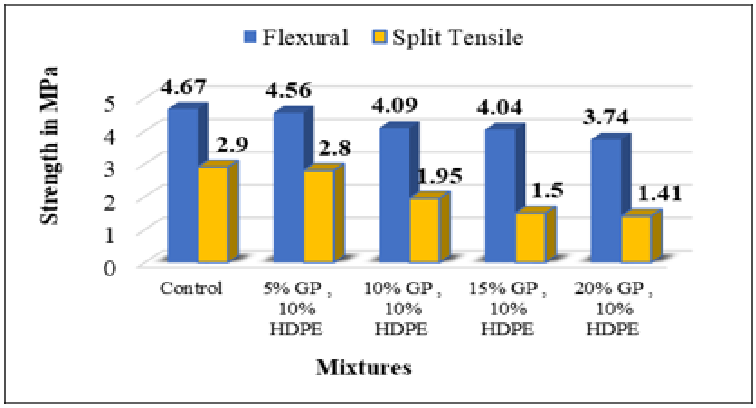

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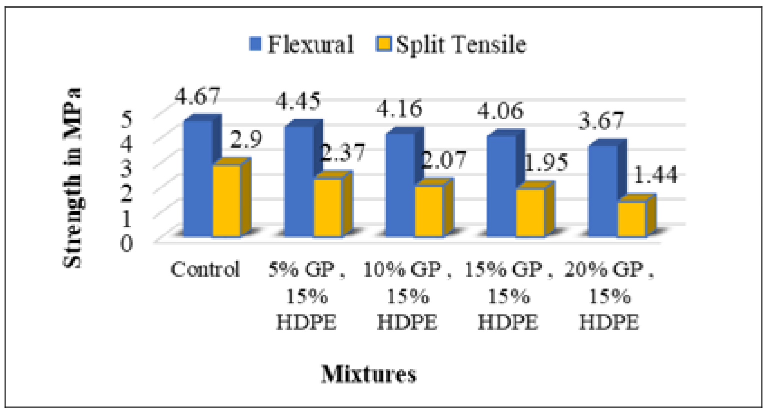

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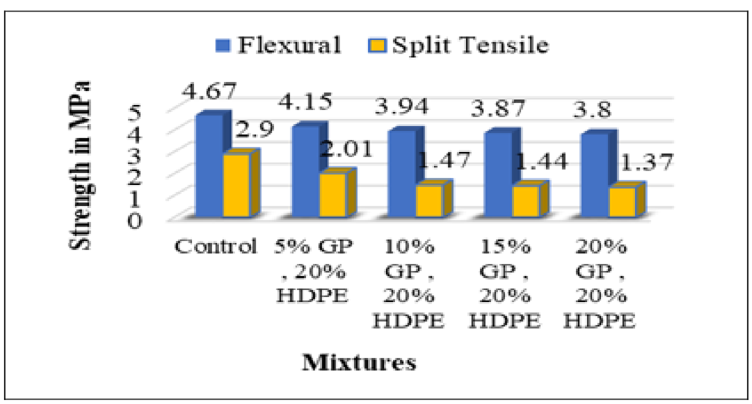


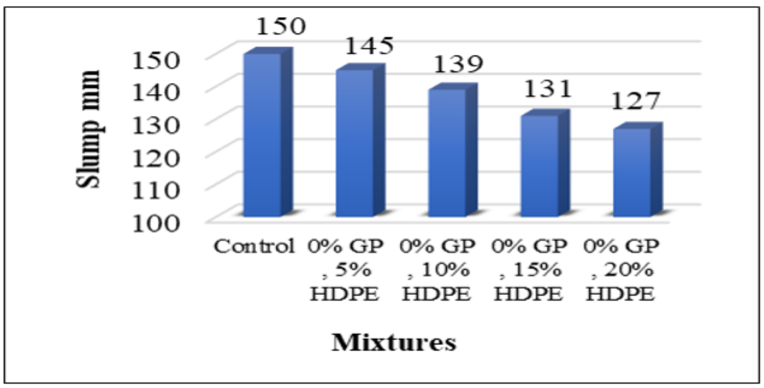
(f)

Figure 6 Flexural and split tensile results of the specimens, (a) 0-20% HDPE replaced, (b) 0-20% GP replaced, (c) 5% HDPE with 5-20% GP, (d) 10%HDPE with 5-20% GP, (e) 15%HDPE with 5-20% GP, (f) 20%HDPE with 5-20% GP

Slump test

The slump test findings, as shown in Figure 7 indicated high workability with a slump value of 149 mm. Substituting fine aggregate with 5% to 20% HDPE in samples S1–S4 resulted in a slight reduction in slump, ranging from 3% to 16% compared to the control mix. This decrease might be attributed to the hydrophobic nature of HDPE, which leads to a loss of matrix integrity and reduced slump. The inability of HDPE to bond with water weakened the concrete mix. Conversely, samples S5–S8, where 5% to 20% WGP replaced the fine aggregate, exhibited an increase in slump value with an increment in WGP percentage. The percent increase in slump ranged from 4.5% to 17% compared to the control mix. This increase results in enhanced matrix integrity (Hossam et al., 2019; Bashar and Ghassan, 2008, Rifat et al., 2018).

When samples S9–S24 replaced fine aggregate with HDPE and cement with WGP, there was a decrease in a slump with an increasing percentage of WGP along with HDPE. The addition of WGP's integrity gain within the matrix was either neutralized or led to an integrity loss due to the combined replacement of HDPE, resulting in a reduction in slump. However, for samples S9–S11, the slump decrease was within the range of 150 mm, while samples S12–24 showed lower slump values. According to the results, it was concluded that the combined replacement of up to 10% WGP and 5% HDPE, as well as up to 10% WGP and 10% HDPE, displayed better slump values compared to the control mix. Additionally, sample S13, where 5% WGP and 10% HDPE were replaced, exhibited a similar dip value as the control mix.



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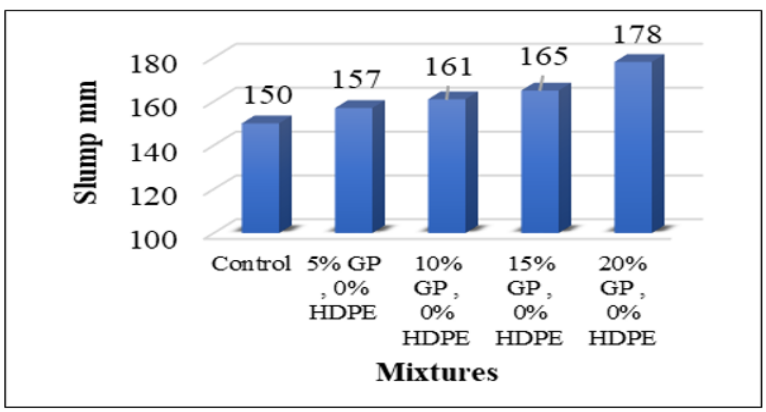

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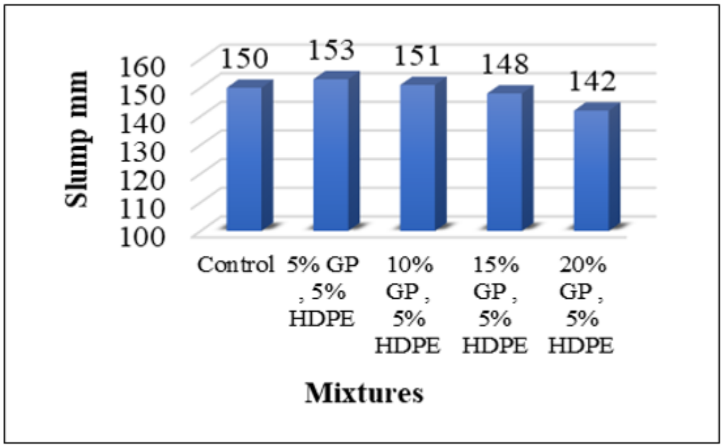
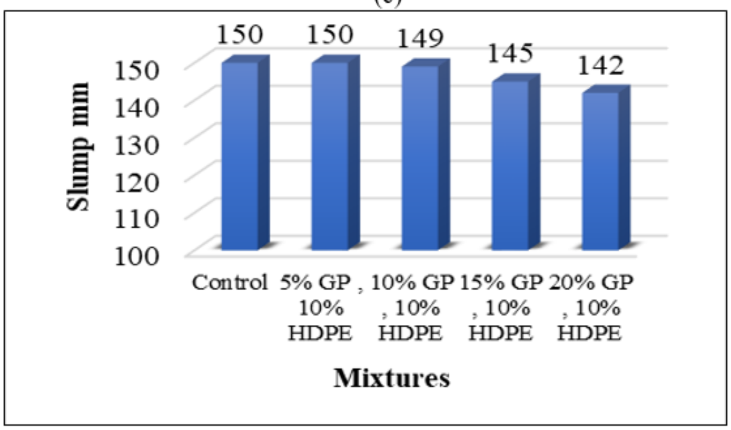


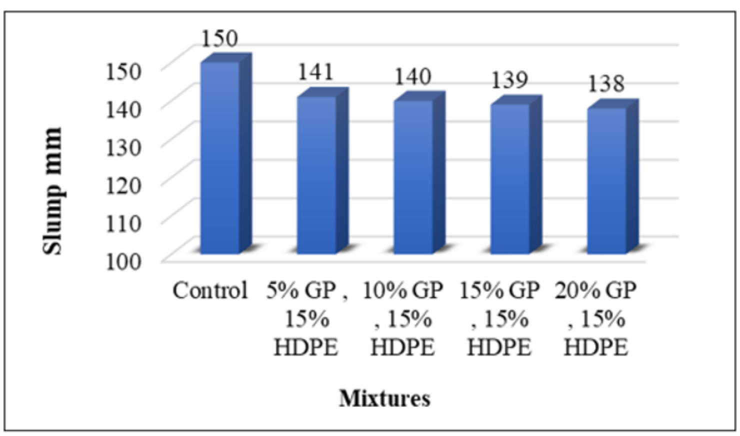
150
153
151
148
142
Slump mm
160
150
140
130
120
110
100
Control
5% GP , 5% HDPE
10% GP , 5% HDPE
15% GP , 5% HDPE
20% GP , 5% HDPE
Mixtures

(c)



150
150
149
145
142
Slump mm
150
140
130
120
110
100
Control
5% GP , 10% HDPE
10% GP , 10% HDPE
15% GP , 10% HDPE
20% GP , 10% HDPE
Mixtures

(d)



150
141
140
139
138
Slump mm
150
140
130
120
110
100
Control
5% GP , 15% HDPE
10% GP , 15% HDPE
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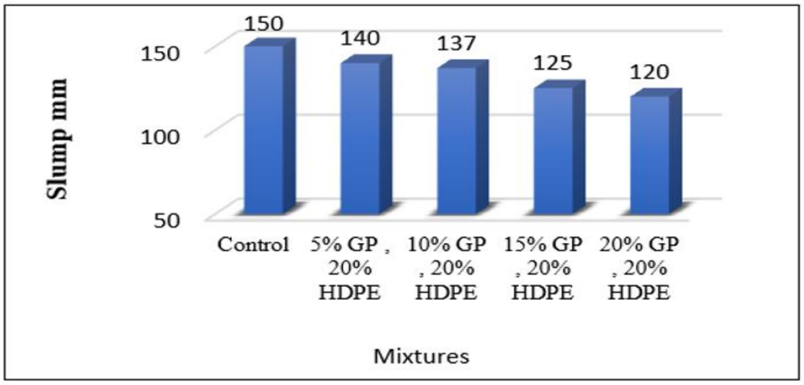
20% GP , 15% HDPE
Mixtures

(e)



(f)

Figure 7 Slump test results of the specimens. (a) 0-20% HDPE replaced, (b) 0-20% GP replaced, (c) 5% HDPE with 5-20% GP, (d) 10%HDPE with 5-20% GP, (e) 15%HDPE with 5-20% GP, (f) 20%HDPE with 5-20% GP

Splitting

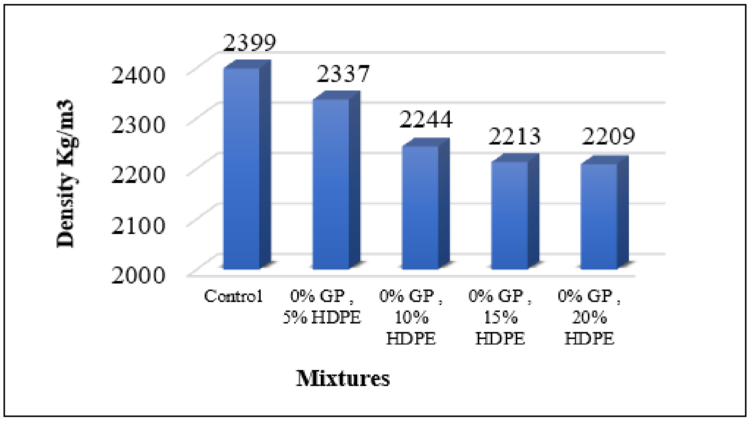
Figure 6 presents the results for both flexural and tensile strength tests. The control blend exhibited a tensile strength of 2.9 MPa. Strengths were reduced in blends S1–S4 containing only HDPE, with the percentage decrease ranging from 1.5% to 6.2%. In contrast, samples S5, S6, and S7 showed higher values than the control mixture. Notably, sample S10, comprising 10% WGP and 5% HDPE, demonstrated the highest value with a percentage increase of 19% compared to the control blend. The lower strength achieved in the HDPE-only blends is attributed to less bonding at the interface transition zone between the HDPE and the fine aggregate.

On the other hand, the slight improvement in strength observed in mixes that contain both HDPE and WGP in comparison to the control could be attributed to the separation of the blends in conditions with higher water content and the decreased ability of HDPE to absorb water. These elements most likely contributed to the overall strength variations that were seen among the different mixes (Sadiqul et al., 2017).

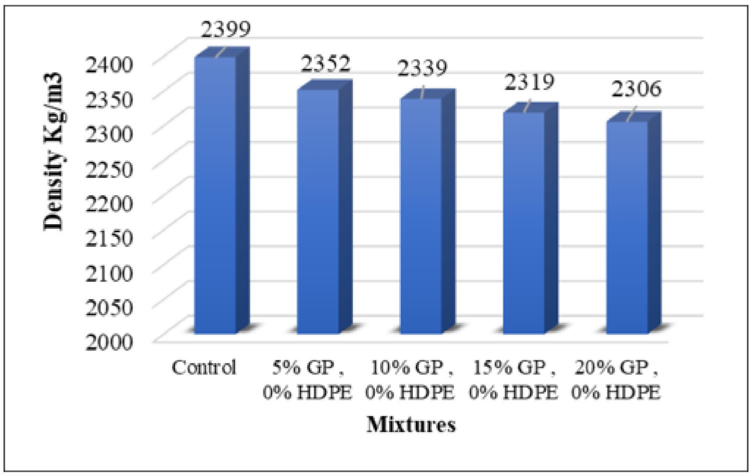
Density of Concrete

Figure 8 presents the dry density test results. The dry density of the control mixture was found to be 2399 kg/m3. The dry density of samples S1 through S4, which had 5% to 20% HDPE replacement, gradually decreased as the HDPE percentage increased. Density reductions from the control mixture varied from 2.6% to 8.2%. As opposed to the control mixture, samples S5 through S8, which had 5% to 20% WGP substituted with cement indicate a slight decrease in density, ranging from 1.9% to 3.9. When both WGP and HDPE were used as replacements in samples S9–S24, the dry density decreased gradually as the percentage of each material increased; the percentage density decreases varied from 0.6% to 8.2% in comparison to the control mix.

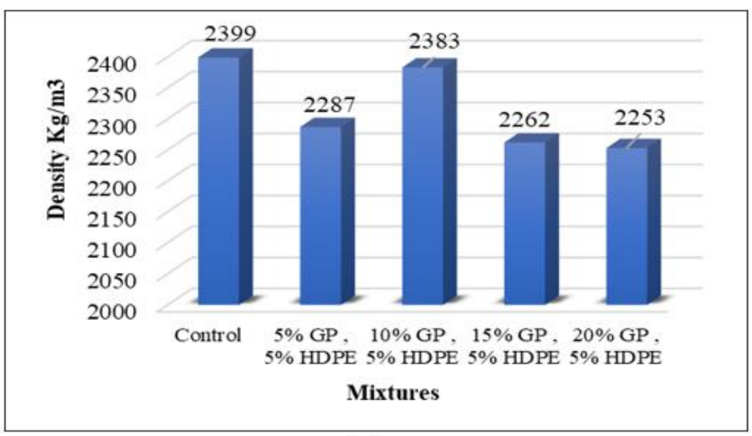
Interestingly, sample S10, which contained 10% WGP and 5% HDPE, had a lower density value of 2383 kg/m3 than the control mix, while sample S4, which had 20% HDPE replacement, had a lower density of 2209 kg/m3 compared to the control mixture of 2399 kg/m3. Concrete dry density is an important metric for assessing the quality of the material and can be affected by several factors such as rock density, air content, and the water-cement ratio. The concrete mix comprising HDPE had a lower unit weight than the mix containing WGP, according to this investigation. By using HDPE as a replacement for sand in the concrete mix, the unit weight can be reduced, while incorporating WGP as a replacement for cement has a minimal impact on the unit weight owing to the lower specific weight of the plastic particles. These findings demonstrate the potential benefits of using HDPE as a coarse replacement in concrete mixtures.


2399
2337
2244
2213
2209
2400
2300
2200
2100
2000
Density Kg/m3
Control
0% GP , 5% HDPE
0% GP , 10% HDPE
0% GP , 15% HDPE
0% GP , 20% HDPE
Mixtures

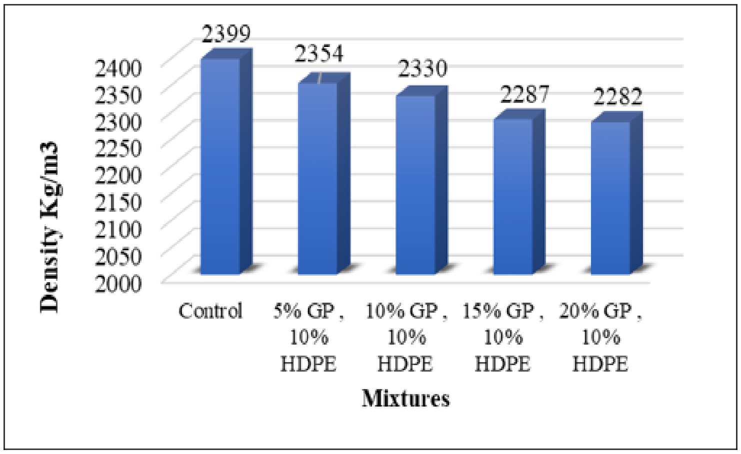
(a)


2399
2352
2339
2319
2306
2400
2350
2300
2250
2200
2150
2100
2050
2000
Density Kg/m3
Control
5% GP , 0% HDPE
10% GP , 0% HDPE
15% GP , 0% HDPE
20% GP , 0% HDPE
Mixtures

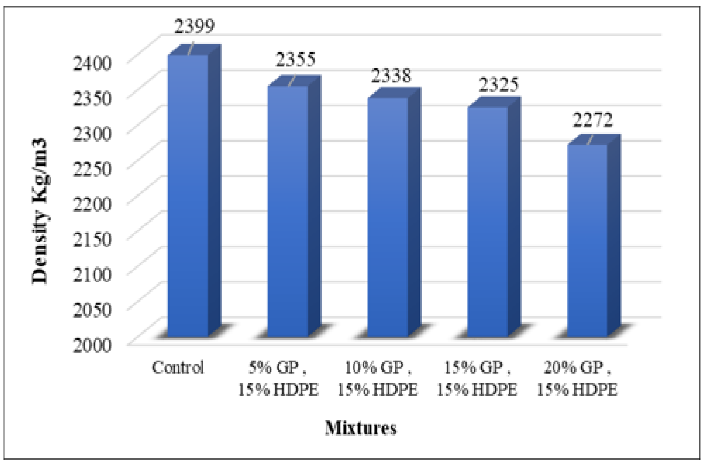
(b)


2399
2287
2383
2262
2253
2400
2350
2300
2250
2200
2150
2100
2050
2000
Density Kg/m3
Control
5% GP , 5% HDPE
10% GP , 5% HDPE
15% GP , 5% HDPE
20% GP , 5% HDPE
Mixtures

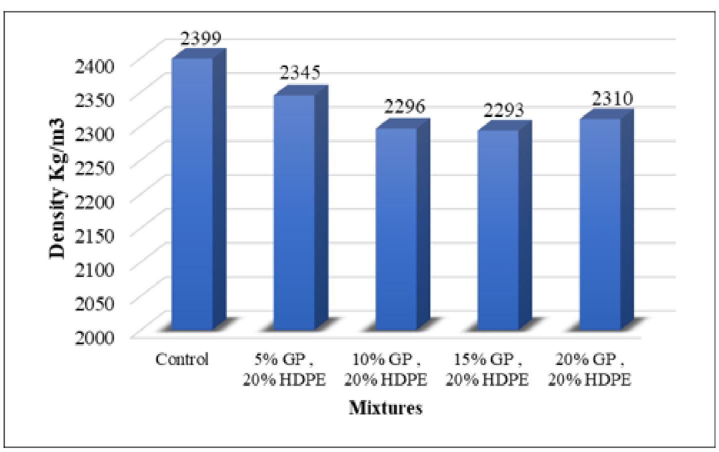
(c)



(d)



(e)



(f)

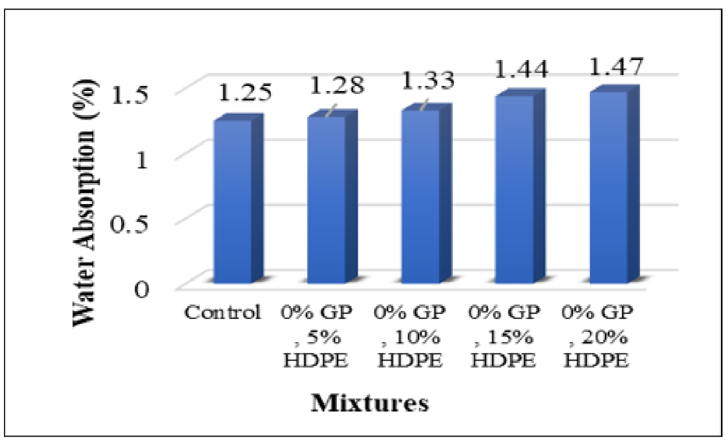
Figure 8 Density results of the specimens, (a) 0-20% HDPE replaced, (b) 0-20% GP replaced, (c) 5% HDPE with 5-20% GP, (d) 10%HDPE with 5-20% GP, (e) 15%HDPE with 5-20% GP, (f) 20%HDPE with 5-20% GP

Water Absorption

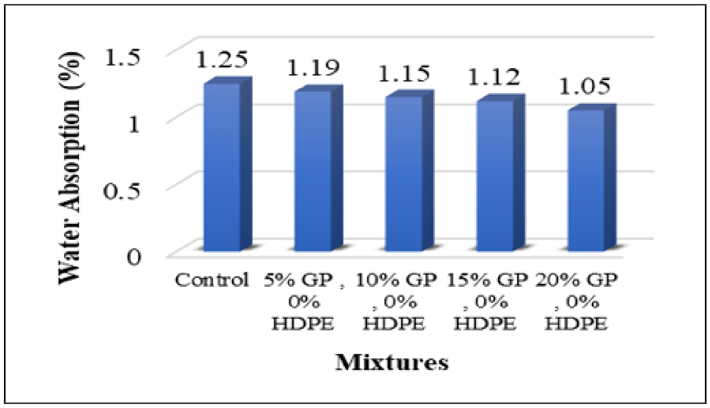
Figure 9 illustrates the outcomes of the water absorption test. The control mix demonstrated a water absorption of 1.25%. For specimens, S1–S4, an incremental rise in water absorption was noted, directly correlated with the percentage increase of HDPE. The percentage of water uptake ranged from 2.4% to 16.1% in comparison to the reference mix. Conversely, specimens S5–S8 displayed a reduction in water absorption as the proportion of WGP increased, aligning with earlier research (Bhat and Bhavanishankar, 2014). The reduction in water absorption ranged from 4.9% to 17.3% compared to the reference mix. For samples, S9–S12, where both WGP and HDPE were used as replacements, the water absorption decreased with the percentage rise of both materials. The percentage decrease in water uptake ranged between 4.9% and 20.2% compared to the control mix.

Similarly, samples S13–S16, substituted with 10% HDPE and 5%–20% WGP, exhibited an initial increase and a subsequent decrease compared to the control blend, based on the percentage increase of WGP. For samples S17–S20, with 15% HDPE and 5%–20% WGP replacements, there was a decrease and then an increase compared to the control mix. Similarly, samples S21–S24, which contained 20% HDPE and 5%–20% WGP, demonstrated a reduction of up to 10.6% and an increase of up to 10.6% in comparison to the control mix. In line with earlier research investigating concrete containing WGP particles, the S12 mix showed the lowest water absorption because of its enhanced mechanical properties. Concrete durability correlates to lower water absorption levels (Bhat and Bhavanishankar, 2014).

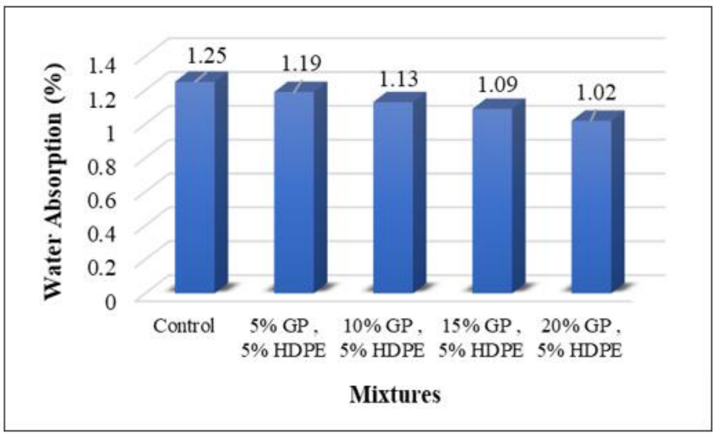
Reducing water absorption improves concrete's long-term performance and durability, especially in hostile environments. The combination of concrete with reduced void volume which included HDPE and WGP in place of fine aggregate and cement, respectively. This result is consistent with earlier research that reported a reduction in water absorption as WGP content increased (Jain et al., 2020). This is partly due to WGP's ability to prevent microcracks from spreading through concrete, which limits the flow of ions and moisture. On the other hand, adding HDPE to the concrete mix as a sand substitute increased the amount of water absorbed by the entire mix. Thus, considering the combined replacement of WGP and HDPE is crucial to attaining the desired properties and concrete performance.



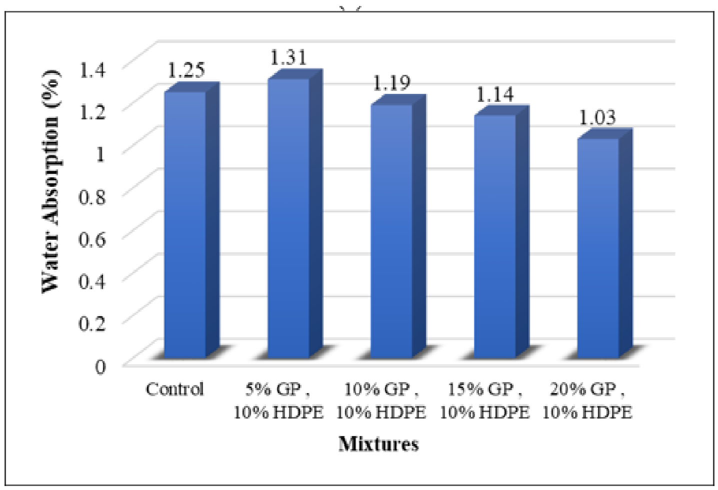
(a)


Water Absorption (%)
1.5
1
0.5
0
1.25
1.19
1.15
1.12
1.05
Control
5% GP , 0% HDPE
10% GP , 0% HDPE
15% GP , 0% HDPE
20% GP , 0% HDPE
Mixtures

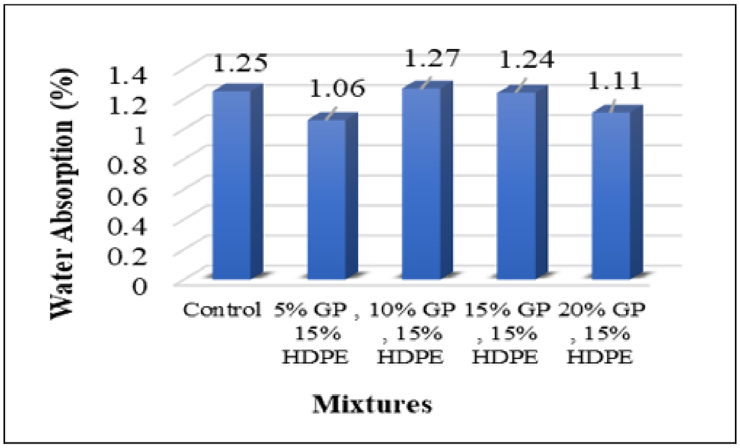
(b)


Water Absorption (%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.25
1.19
1.13
1.09
1.02
Control
5% GP , 5% HDPE
10% GP , 5% HDPE
15% GP , 5% HDPE
20% GP , 5% HDPE
Mixtures

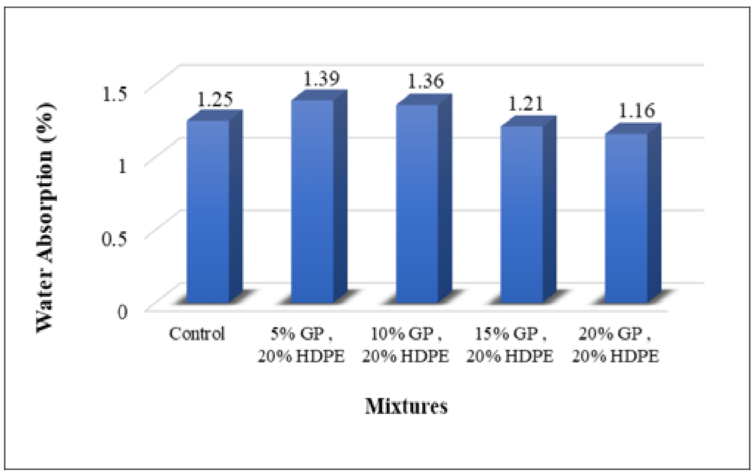
(c)


Water Absorption (%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.25
1.31
1.19
1.14
1.03
Control
5% GP , 10% HDPE
10% GP , 10% HDPE
15% GP , 10% HDPE
20% GP , 10% HDPE
Mixtures

(d)



(e)



(f)

Figure 9 The water absorption samples: (a) substituting 0-20% HDPE, (b) substituting 0-20% GP, (c) substituting 5% HDPE with 5-20% GP, (d) substituting 10% HDPE with 5-20% GP, (e) substituting 15% HDPE with 5-20% GP, and (f) substituting 20% HDPE with 5-20% GP

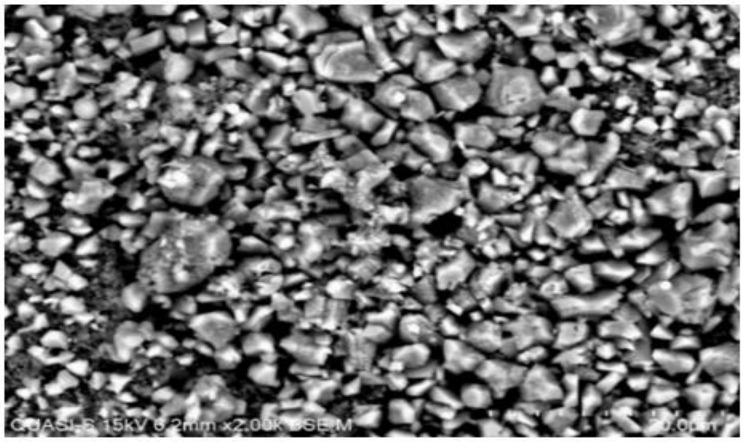
Microstructure analysis

Scanning Electron Microscope (SEM)

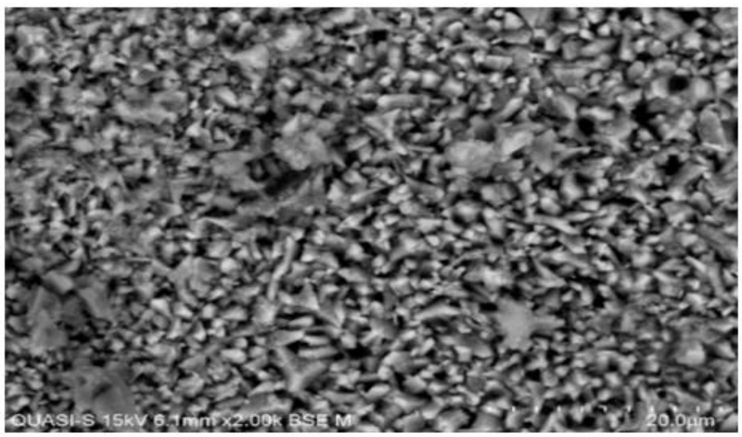
Electron microscopy (SEM) is used for analyzing the microscopic structure of materials made of concrete. The specimens' morphological properties were investigated using the Hitachi Model S-3000H (Han et al., 2018). Figure 10 depicts the surface characteristics of the optimized and control concrete samples after 28 days of curing, as seen in pictures collected from SEM and energy dispersive X-ray analysis elements as presented in (Table 4). The control concrete sample unfolds, exhibiting a surface that appears compact with intermittent voids, a consequence attributed to the intricate hydration process of cement embedded within the concrete matrix. the optimized concrete sample, revealing a markedly denser surface with notably fewer voids.

This transformation in surface morphology is directly linked to the strategic integration of waste glass powder (WGP) into the concrete mixture. Significant improvement as a consequence of WGP incorporation is indicated by the optimized concrete specimen's noticeable densification and reduction in voids. The microstructure becomes consistent with evenly spaced glass particles as a result of this densification, strengthening the link between the glass, sand, and cement. Previous research demonstrates how important WGP is for maintaining the integrity of concrete. WGP integration enhances mechanical properties by fortifying the matrix-aggregate link.

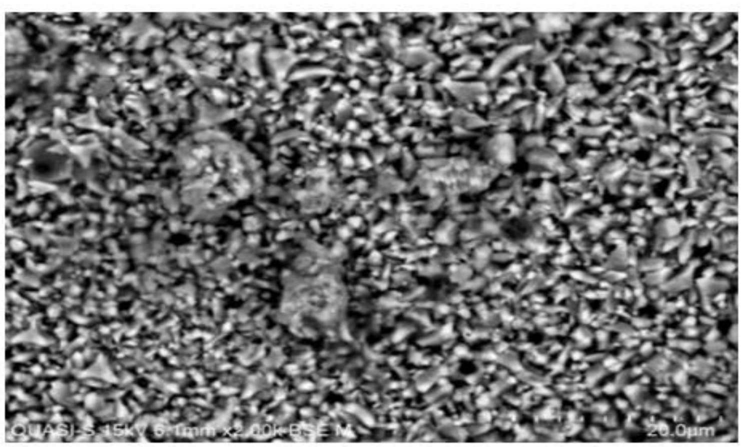
WGP's pozzolanic reaction fills the C-S-H gel's capillary holes, reducing voids and densifying the microstructure. The optimized concrete sample with high-density polyethylene (HDPE) integration, has denser sections and is compact with some voids.



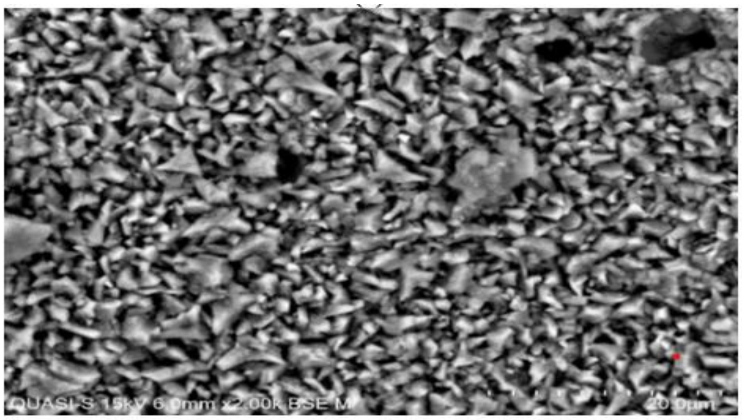
(a)



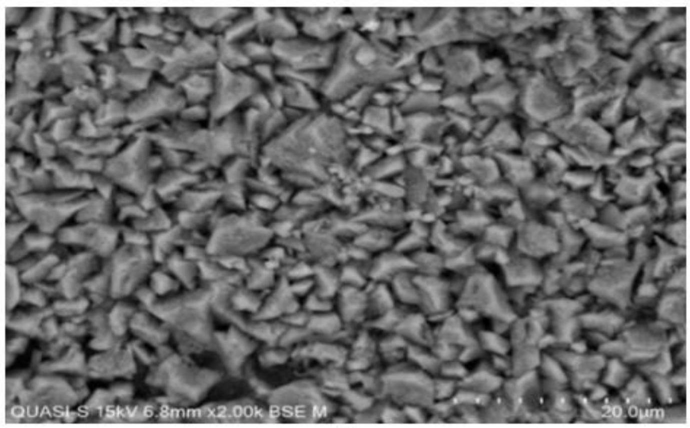
(b)



(c)



(d)



(e)

Figure 10 SEM images of the (a) control mix (b) 5% WGP (c) 10% WGP (d) 15% WGP (e) 10% WGP – 5% HDPE

The SEM analysis revealed that the optimized concrete sample, which incorporated waste glass powder (WGP), exhibited a denser surface with fewer voids compared to the control mix. This densification, attributed to the pozzolanic reaction of WGP filling capillary pores, contributes to reduced porosity and improved bonding between the matrix and aggregates. These microstructural improvements align with the observed increase in compressive strength of the optimized concrete, as the reduced voids and enhanced bonding lead to a more cohesive and stronger material. Specifically, the optimized mix demonstrated up to a 13.6% increase in compressive strength compared to the control, directly correlating with the observed microstructural densification.

On the other hand, the SEM images of the HDPE-containing concrete revealed a more compact surface but still showed some voids and less adherence between the HDPE particles and the cement matrix. This weaker bonding between the HDPE and cement, similar to the behavior of natural aggregates, results in a less cohesive microstructure, which likely contributes to the reduction in compressive strength observed with higher HDPE content. The porosity and non-uniform hydration products seen in the SEM analysis of HDPE mixes are indicative of inadequate hydration, which is reflected in the mechanical property results where HDPE mixtures showed lower strength.

Table 4 Element weights were determined by analyzing concrete samples at a 28-day cure age

Element	Control	10% WGP	5% HDPE
C	13.83	14.18	14.76
O	48.88	45.28	47.53
Mg	0.63	0.37	0.52

Al	0.42	0.94	0.68
Si	0.62	1.83	0.83
S	35.62	0.26	-
K	-	0.52	-
Ca	-	35.24	35.69
Fe	-	0.68	-
C	-	0.69	-
Total	100%	100%	100%

X-ray Diffraction

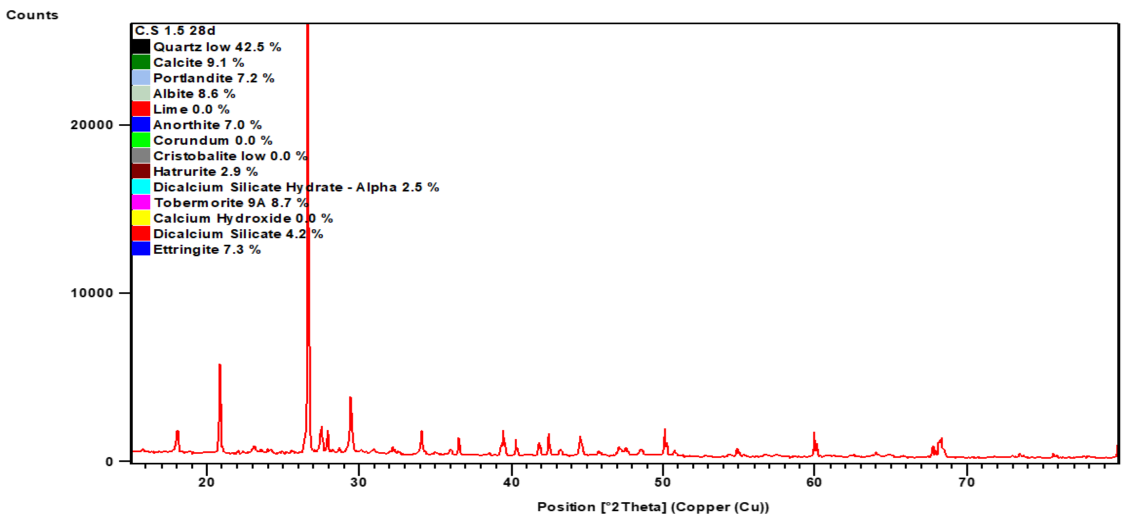
The X-ray diffractograms in Figure 11 revealed the mineralogical compositions of concrete samples due to hydration and pozzolanic activities. The optimized concrete exhibited a peak corresponding to dicalcium silicate (Ca2SiO4), indicating pozzolanic activity. Silicon dioxide (SiO2) also displayed high intensity in its crystalline phase. This suggests that the improvement in C-S-H capillary pores was due to the pozzolanic reaction, which enhanced strength. Additionally, the finer granulometry of WGP increased pore filling and reduced porosity. Table 5 XRD results present that the 28-day control concrete sample comprises cementation products, contains quartz (42.5%), dicalcium silicate hydrate (4.2%), ettringite (7.3%), portlandite (7.2%), calcite (9.1%), albite (8.6%), anorthite (7%), tobermorite 9A (8.7%), Sodium Carbonate - Alpha, Ht (2.5%), and Hatruite (2.9%).

The presence of 42.5% quartz confirms the use of river sand as fine aggregate in the control sample. The treated concrete samples exhibited higher values of quartz, calcite, portlandite, albite, and anorthite compared to the control, leading to enhanced strength and performance. The optimized concrete mix with WGP showed higher intensities of pozzolanic compounds like dicalcium silicate and silicon dioxide, which are associated with the formation of C-S-H gels that contribute to strength. These mineralogical changes in the optimized mix correlate with the increased mechanical strength.

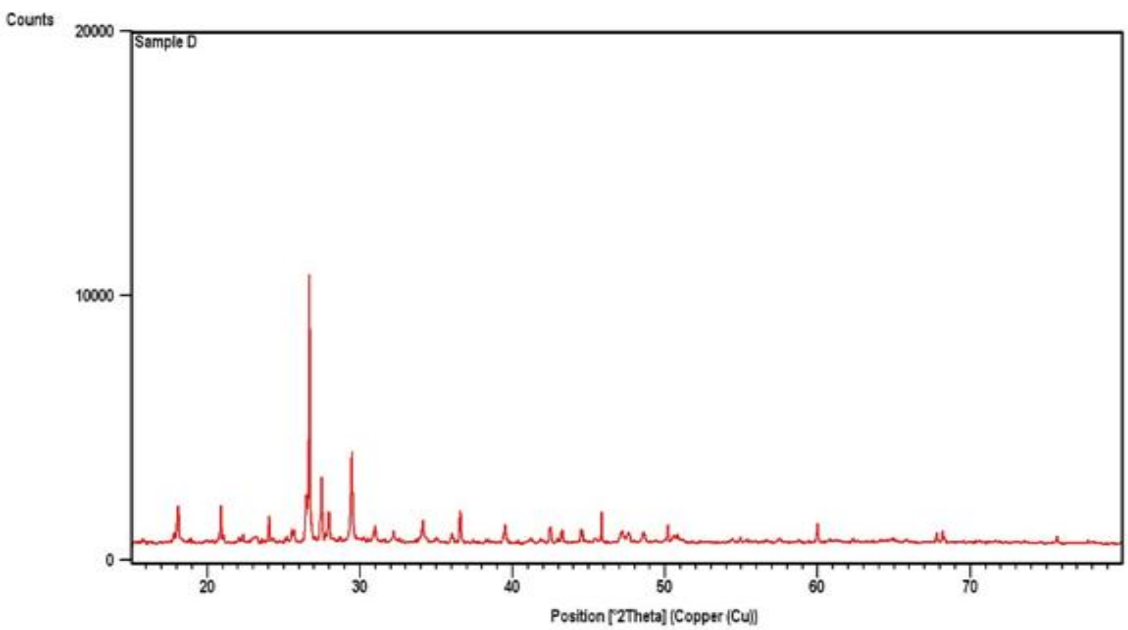
Table 5 XRD results

No	Compound Name	Semi Quant [%]				
		A	B	C	D	E
1	Quartz	42.5 %	3 %	5 %	6 %	6 %
2	Calcite	9.1 %	3 %	1 %	1 %	2 %
3	Portlandite	7.2 %	2 %	1 %	1 %	1 %
4	Albite	8.6 %	6 %	5 %	10 %	8 %
5	Anorthite	7 %	8 %	8 %	16 %	11 %
6	Ettringite	7.3 %	3 %	19 %	8 %	6 %
7	Dolomite	0 %	1 %	4 %	3 %	1 %
8	Gismondine	0%	21 %	18 %	22 %	16 %
9	Augite	0%	2 %	3 %	4 %	4 %
10	Dicalcium Silicate	4.2 %	3 %	1 %	1 %	2 %
11	Tobermorite 9A	8.7	13 %	9 %	6 %	3 %
12	Suolunite	0 %	3 %	4 %	1 %	3 %
13	Cristobalite	0 %	4 %	4 %	2 %	2 %
14	Feldspar	0 %	4 %	5 %	8 %	21 %
15	Hornblende	0 %	4 %	3 %	3 %	7 %
16	Sodium Carbonate - Alpha, Ht	2.5 %	3 %	2 %	2 %	2 %
17	Hatruite	2.9 %	0 %	0 %	0 %	0 %
18	Tricalcium silicate oxide	0 %	16 %	8 %	6 %	4 %
	Total	100 %	99 %	100 %	100 %	99 %

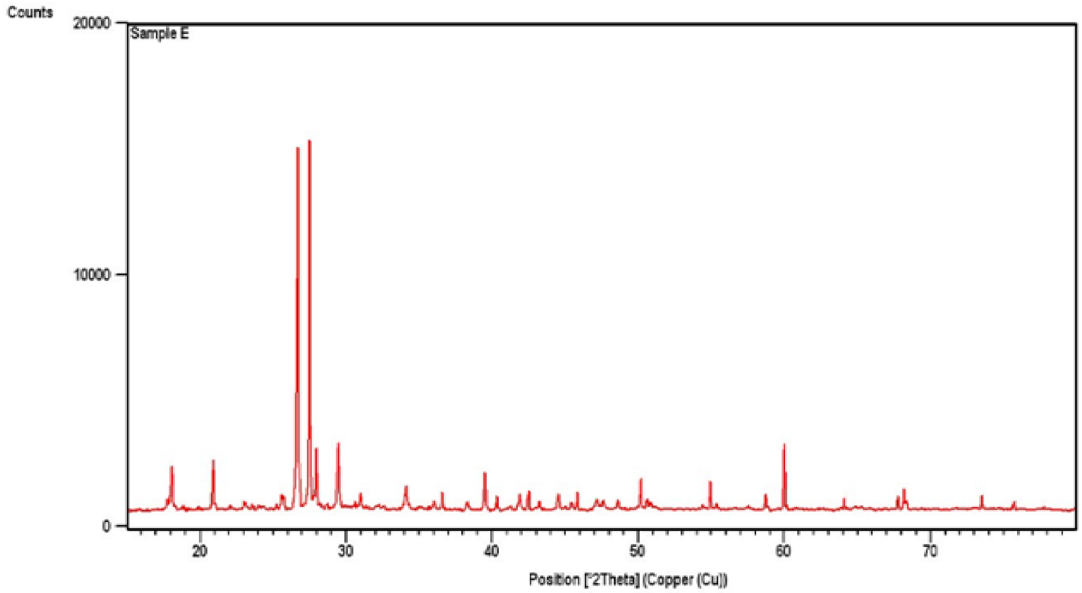
A) Control sample, B) 5% Glass powder, C) 10% Glass powder, D) 15 % Glass powder, E) 10% Glass powder + 5% waste HDPE.


Counts
C.S 1.5 28d
Quartz low 42.5 %
Calcite 9.1 %
Portlandite 7.2 %
Albite 8.6 %
Lime 0.0 %
Anorthite 7.0 %
Corundum 0.0 %
Cristobalite low 0.0 %
Hatrurite 2.9 %
Dicalcium Silicate Hydrate - Alpha 2.5 %
Tobermorite 9A 8.7 %
Calcium Hydroxide 0.0 %
Dicalcium Silicate 4.2 %
Ettringite 7.3 %
20000
10000
0
20
30
40
50
60
70
Position [°2Theta] (Copper (Cu))

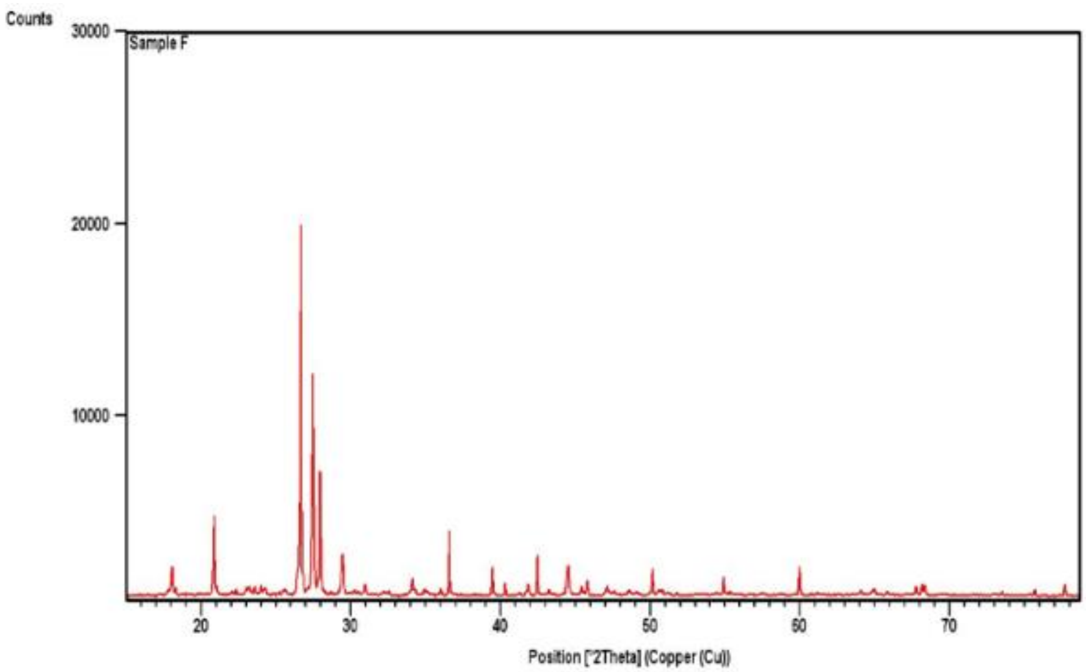
(a)


Counts
20000
Sample D
10000
0
20
30
40
50
60
70
Position [°2Theta] (Copper (Cu))

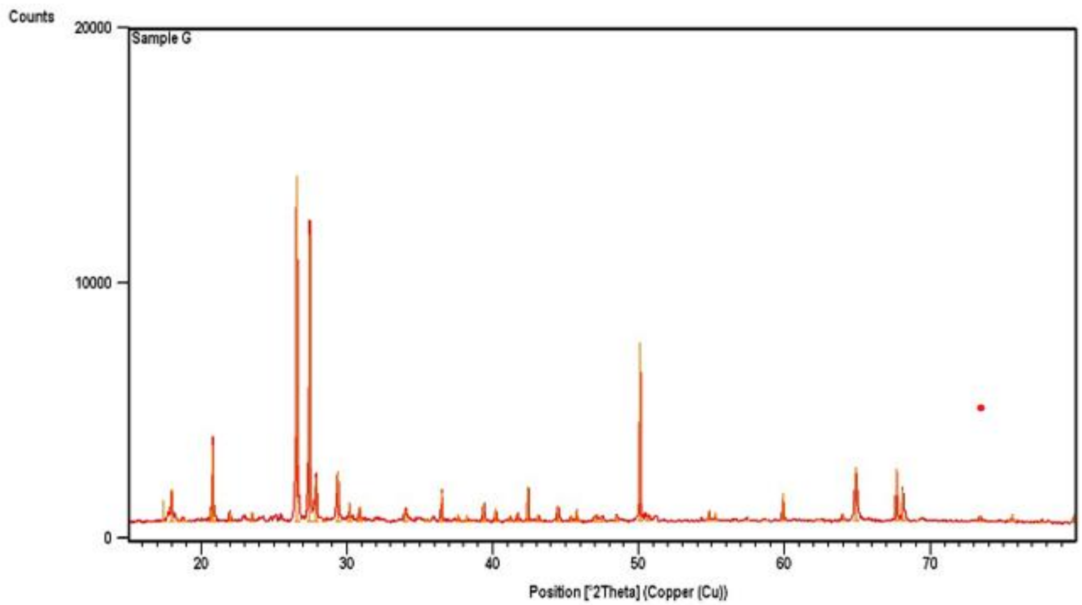
(b)


Counts
20000
10000
0
Sample E
20
30
40
50
60
70
Position [°2Theta] (Copper (Cu))

(c)


Counts
30000
20000
10000
Sample F
20
30
40
50
60
70
Position [°2Theta] (Copper (Cu))

(d)



(e)

Figure 11 XRD results of (a) control mix (b) 5% glass powder mix (c) 10% glass powder mix (d) 15% glass powder mix (e) 10% glass powder + 5% black high-density polyethylene beads

4. CONCLUSION

This study aimed to assess the impact of waste glass powder (WGP) and high-density polyethylene (HDPE) as alternative materials to partially substitute cement and fine aggregate in concrete. The findings revealed that incorporating 10% WGP and 5% HDPE significantly improved the compressive, flexural, and splitting strengths of the concrete. While the inclusion of WGP led to a clear enhancement in flexural and splitting strength, higher HDPE replacement portions caused a decline in these properties. Increasing HDPE content as a fine aggregate led to strength reduction and higher water absorption, while using WGP as a partial cement substitute improved strength and decreased water absorption.

The optimized concrete mix with 10% WGP and 5% HDPE demonstrated substantial performance development, including a 12.7 MPa increase in compressive strength, a 19.8% rise in flexural strength, and a 17.3% boost in tensile strength. Although the use of HDPE reduced slump performance, WGP inclusion improved workability, with the optimized mix achieving a slump similar to that of the control concrete. Moreover, concrete density decreased with higher HDPE content than with WGP, as the low density of HDPE reduced interfacial adhesion and bonding of the cement matrix. However, the combined use of WGP and HDPE mitigated these effects, as WGP efficiently filled the pores introduced by HDPE, reducing porosity and improving strength.

The study concludes that incorporating WGP and HDPE into concrete is both practical and beneficial for improving its mechanical and durability properties when substitute rates remain below 10%. Exceeding this threshold resulted in diminished performance. This strategy not only provides an effective means of waste management but also contributes to the production of eco-friendly concrete. The application of HDPE-modified concrete is particularly suited for non-load-bearing structures, such as partitions and pavements, where high compressive strength is less critical. For further advancements, future research should focus on optimizing these replacement proportions by examining the long-term behavior and performance of such concrete under diverse environmental conditions.

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Author Contributions

Conceptualization, Al-Mashhadani Duraid Ali Jasim; Investigation, Al-Mashhadani Duraid Ali Jasim; Methodology, Al-Mashhadani Duraid Ali Jasim and Leong Sing Wong; Supervision, Leong Sing Wong; Validation, Midhin A. K. Midhin, and Mohammed Chyad Liejy; Visualization, Midhin AK Midhin, and Mohammed Chyad Liejy; Writing – original draft; Writing – review & editing, Al-Mashhadani Duraid Ali Jasim and Leong Sing Wong. All authors have read and agreed to the published version of the manuscript.

Informed consent

Not applicable.

Ethical approval

Not applicable.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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