construction materials

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Experimental Study on the Suitability of Waste Plastics and Glass as Partial Replacement of Fine Aggregate in Concrete Production

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Abstract: Solid waste management is a major environmental challenge, especially in developing countries, with increasing amounts of waste glass (WG) and waste plastic (WP) not being recycled. In Ethiopia, managing WG and WP requires innovative recycling techniques. This study examines concrete properties with WG and WP as partial replacements for fine aggregate. Tests were conducted on cement setting time, workability, compressive strength, splitting tensile strength, and flexural strength. Concrete of grade C-25, with a target compressive strength of 25 MPa, was prepared by partially replacing fine aggregate with WP and WG. The mechanical properties were evaluated after 7 and 28 days of curing. At a 20% replacement level, workability decreased at water–cement ratios of 0.5 and 0.6 but remained stable at 0.4, leading to the selection of the 0.4 ratio for further testing. A 10% replacement of fine aggregate, using a ratio of 3% WP and 7% WG, was found to be optimal, resulting in an increase in compressive strength by 12.55% and 6.44% at 7 and 28 days, respectively. In contrast, a 20% replacement led to a decrease in compressive strength by 14.35% and 0.73% at 7 and 28 days, respectively. On the 28th day, the splitting tensile strength at the optimal replacement level was 4.3 MPa, reflecting an 8.5% reduction compared to the control mix. However, flexural strength improved significantly by 19.7%, from 12.46 MPa to 15.52 MPa. Overall, the incorporation of WG and WP in concrete enhances flexural strength but slightly reduces splitting tensile strength.

Keywords: fine aggregate replacement; recycling; waste glass; waste plastics

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1. Introduction

The amount of waste generated by various industrial sectors is steadily increasing, posing a major environmental problem. It is a common objective of sustainable global development goals to fight the climate crisis by recycling waste materials to reduce the volume of solid waste at disposal sites [1–7]. Currently, about 8.3 billion metric tons of plastic are generated globally and this is expected to increase to 12 billion by 2050. However, only 9% of these are recycled, and 6.3 billion are accumulated in landfills or sloughing off in the natural environment. Moreover, as of 2018, the glass industry reported recycling around 27 million metric tons globally, accounting for about 21% of total glass production [8]. Therefore, solid waste reuse in the construction industry is gaining attention in developed countries. Currently, the scarcity of construction materials and excessive disposal of waste products are the difficulties experienced globally that need a rapid and permanent solution [9,10]. Notably, this process has led scholars to tackle the issue of finding suitable eco-friendly construction materials and handle environmental matters simultaneously [11].

Recently, there has been some evidence of waste materials and by-products used in construction materials. However, recycling waste as an alternative construction material is used significantly less in developing countries [12]. The usage of these materials aids in their integration into cement, concrete, and other construction materials but also assists in lowering the cost of cement production by reducing energy consumption and improving environmental protection from potential carbon emissions [13–16].

Recycling waste glass and plastic has always been an issue globally, even though the recycling rate of glass is relatively high compared with plastics [17]. A lot of research has been conducted on recycling plastic waste in mortar [18–22] and concrete [23–26]. Other studies have been conducted on the recycling of waste glass in concrete as a fine aggregate replacement [1,17,27], coarse aggregates as an additive [27–31], partial replacement of cement [32–35], and as fine aggregates [36] in mortar. In other studies, fine aggregates used in concrete mixtures are substituted in proportions by shredded plastics and glass, and the optimal amount is determined at which greater strength is attained [37–39]. Concrete from plastic and glass wastes has several benefits including being lightweight, robust, simple to shape, and customized to various customer needs [40].

The use of glass wastes as fine aggregates improves the physical and mechanical properties of concrete by reducing the density, and they are effective in controlling the structure's weight for stability purposes [41]. On the other hand, crushed glass contains engineering characteristics of an angular and somewhat elongated shape. This situation creates a higher internal friction angle, improving the interlocking between different ingredients of concrete particles. Partial replacement of waste glass does not significantly affect the workability of the concrete [42]. However, it has been shown that the compressive strength decreases by almost 49% with a 60% of WG [42].

On the other hand, the addition of waste glass as fine aggregates increases the mechanical properties of mortar [36]. Replacing the natural sand with recycled high-density polyethylene (HDPE) aggregates increased the axial deformation capability of mortar and reduced the density [21]. Waste plastic as coarse aggregates in the concrete also increases the workability of concrete [43]. The rise in slump indicates that more water was available from the mix due to decreased absorption by reducing the percentage volume of natural aggregates and low water absorption by recycled plastics [44,45]. Many authors reported a gradual decrease in the compressive strength by increasing the percentage of waste plastic [46–48]. Their findings show that the addition or partial replacement of WG and WP has positive and negative effects on the concrete's fresh and hardened properties. However, limited research is available on the combination of WG and WP in concrete as a partial replacement for fine aggregates. The primary aim of this research is to investigate the properties and performance of concrete produced using waste glass (WG) and waste plastic (WP) as partial replacements for fine aggregate. This study seeks to evaluate the potential benefits and challenges of incorporating these waste materials into concrete mixtures, including their impact on the mechanical properties. By exploring these factors, the research aims to contribute to more sustainable construction practices and the effective utilization of waste materials.

2. Materials and Methods

Comprehensive experimental tests were conducted to study the characteristics and strength properties of the partial replacement of fine aggregates with plastic and glass waste on concrete's fresh and hardened properties. Potential waste glass quantities were collected from empty glass containers and various building and construction remnant materials commonly used for laboratory procedures. The waste glass was crushed into fine pieces that resembled the size of sand. On the other hand, samples of granulated plastic waste, mostly soda and water bottles, were collected from a dumpsite. Waste plastics should be cleaned before use to remove debris and impurities that could alter the hydration and bonding of the cement paste. The plastic samples were selected to fit the sieve's size requirements at the laboratory.

The proportion by weight of all constituents (aggregates, cement, plastics, glass, and water) was kept constant in all the mixes. The ACI mix design method arrived at the right combination of cement, fine aggregate, coarse aggregate, and water for C-25 grade concrete. Finally, different experiments were conducted on concrete properties with various mixing and curing parameters. For this study, the ratios of the weight of waste plastics to glass used were 3:7, 6:14, and 10:20. The optimum mix ratio was determined.

2.1. Cement

Ordinary Portland cement (OPC) with a grade of 42.5 N manufactured by the Derba Midroc Cement PLC in Salale Zone, Oromia Regional State, Ethiopia was selected for this study. The physical and mechanical properties were studied using the requirements specified by ASTM and are presented in Table 1. Cement pastes with different water–cement ratios generally have other setting times. Therefore, it does not seem apparent at first which setting time to use. The setting time of a cement paste with a typical consistency is referred to as the setting time of cement paste by convention [49]. The initial setting time is the duration of cement paste related to 25 mm penetration of the Vicat needle into the paste 30 s after it is released.

Table 1. Physical properties of Derba cement.

Physical Properties	Test Results	Recommended Value
Consistency (%)	31	26–33 [49]
Initial Setting Time (min)	52	more than 45 min [50]
Final Setting Time (min)	320	not more than 375 [50]

In contrast, the final setting time is related to zero penetration of the Vicat needle into the paste [49]. The standard consistency for hydraulic cement refers to the amount of water required to make a neat paste of satisfactory workability. The Vicat apparatus was used to assess the paste's resistance to penetration by applying a 300-gram plunger to its surface. The mechanical property of the cement used in this study is shown in Table 2.

Table 2. Mechanical property of Derba cement.

Mechanical Property	Test Results
3rd day compressive strength (MPa)	23.20
7th day compressive strength (MPa)	33.40
28th day compressive strength (MPa)	45.70

2.2. Aggregate

The fine aggregate (river sand) used for this research work was brought from suppliers of Jimma town, Ethiopia, and was originally from Gambela, Ethiopia, and crushed coarse aggregate was bought from the crusher site located in Jimma town. Aggregate grain size distribution or gradation is one of the properties of aggregates that influences the quality of concrete. Therefore, fine aggregates and coarse aggregates with gradation satisfying the grading requirement of the ASTM standard [51], shown in Figures 1 and 2, were used throughout the experiment.

Therefore, the grain size distribution curve exhibits a fine aggregate sample employed for this research task as a well-graded type of aggregate. The percentage passing of fine aggregate runs in the lower and upper limit of the standard requirement gradation curve.

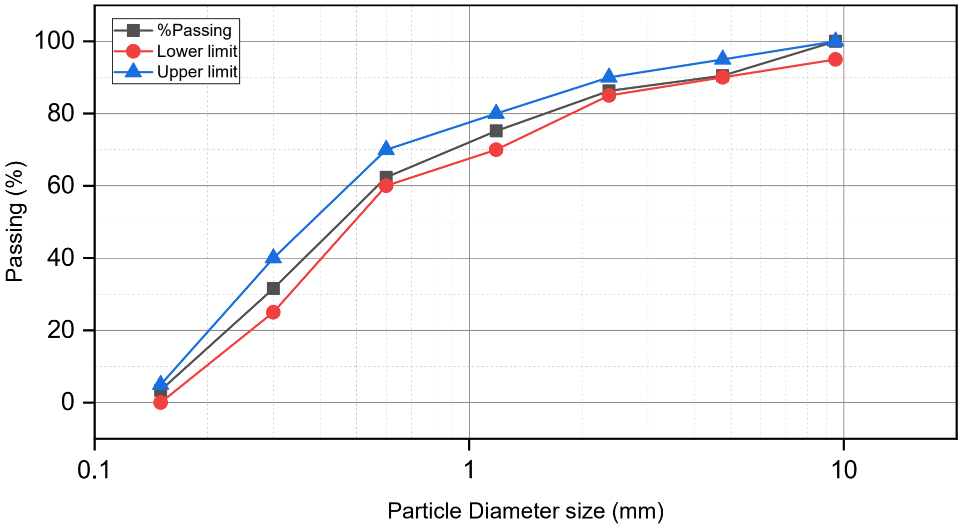

Figure 1. Grain size distribution curve of fine aggregate.

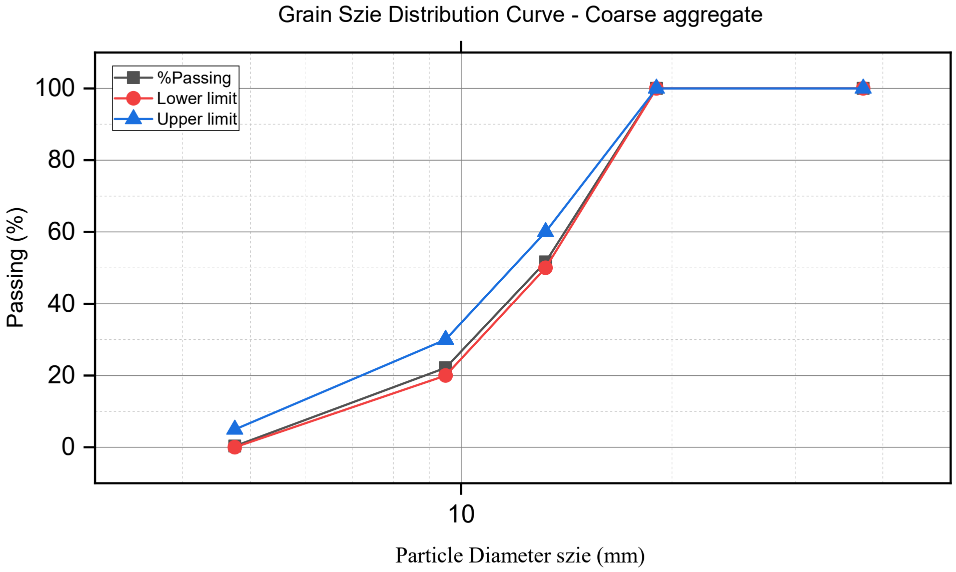

Figure 2. Grain size distribution curve of coarse aggregate.

2.3. Waste Plastics

Forty-three (43) kg samples of the waste plastic particles, mostly soda and water bottles, were collected from plastic disposed in the Jimma town bore dumping site in Ethiopia. high-density polyethylene (HDPE) and Polyethylene Terephthalate (PET) are two types of commonly used plastics made for everyday use. For this study, PET types of plastics were selected since they can be found in high volumes in dumpsites relative to others. The collected plastics were cleaned from impurities with tap water and then air-dried. The air-dried sample was melted at 130 °C, cooled to make it suitable for crushing, and converted to a fine-sized aggregate. The production process of the fine waste plastic is illustrated in Figure 3. Finally, a sieve analysis was conducted and the required size of the plastic aggregate was determined, as illustrated in Figure 3.

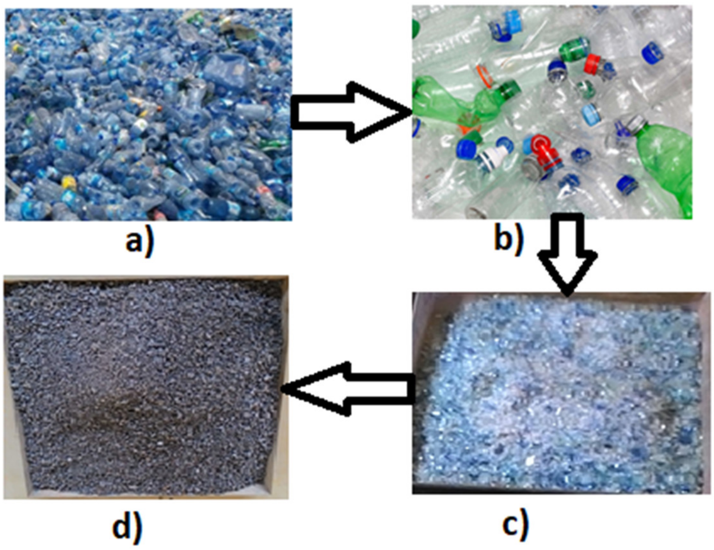

Figure 3. Fine waste plastic preparation process: (**a**) collection, (**b**) cleaning, (**c**) crushing, (**d**) melted and grinded.

The physical properties of the plastic and glass waste are summarized in Table 3.

Table 3. Physical properties of plastic and glass waste.

Properties	**Test Results**		**ASTM Code Standards [52]**
-	**Plastic Waste**	**Glass Waste**	**Recommended**
Fineness modulus (FM)	2.52	2.56	-
The nominal maximum size, (mm)	0.075–4.00	0.075–4.00	-
Specific gravity (SSD basis)	1.09	2.62	2.3–2.9
Unit weight, (kg/m^3)	65	2450	1280–1920
Water absorption capacity, (%)	0.00	0.01	0.4–4.0

The grain size distribution curve of fine waste plastics is illustrated in Figure 4.

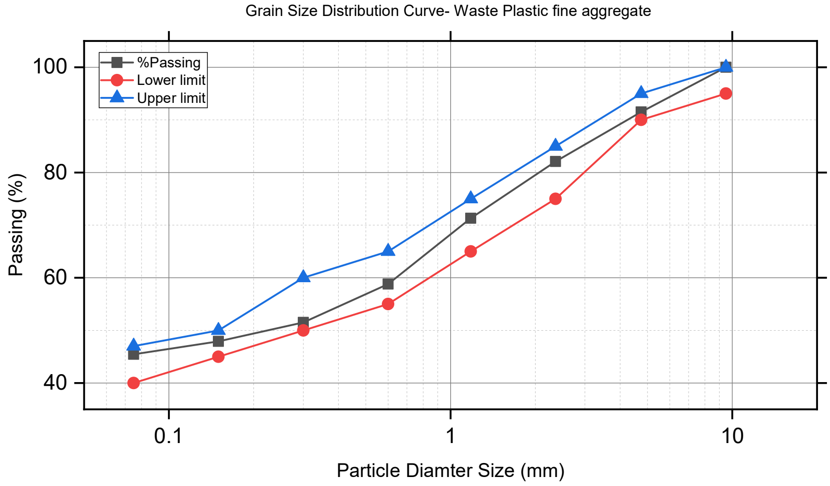

Figure 4. Grain size distribution curve of fine- waste plastics.

2.4. Waste Glass

Seventy-two (72) kg of waste glass materials was used throughout this experimental study, gathered from the disposals of reconstruction and building demolition projects in the Jimma town bore solid-waste dumping site. Soda-lime-type glass was used for the investigation throughout this research study among different glasses. For this task, the collection of waste and glass focused on a 'bore' dumping site in Jimma town. The collected waste glass was contaminated with impurities that could have altered the glass's chemical and physical properties. Therefore, the waste glass was cleaned with pure water to remove impurities. Then, the cleaned waste glass was ground into a fine aggregate size manually using a hammer.

Finally, the crushed waste glass was sieved, and the required size was obtained, as shown in Figure 5.

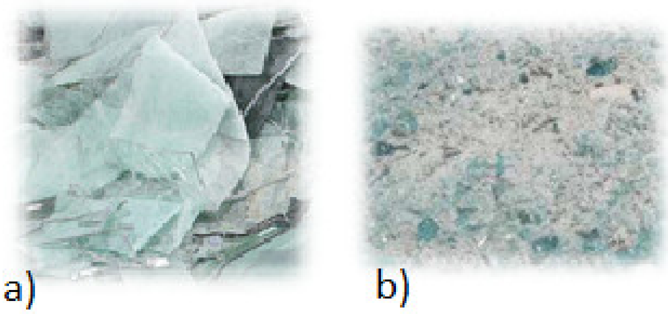

Figure 5. Granulated glass particles used for testing: (**a**) collected sample, (**b**) cleaned, crushed, and sieved waste glass.

The grain size distribution curve of the fine waste glass is illustrated in Figure 6.

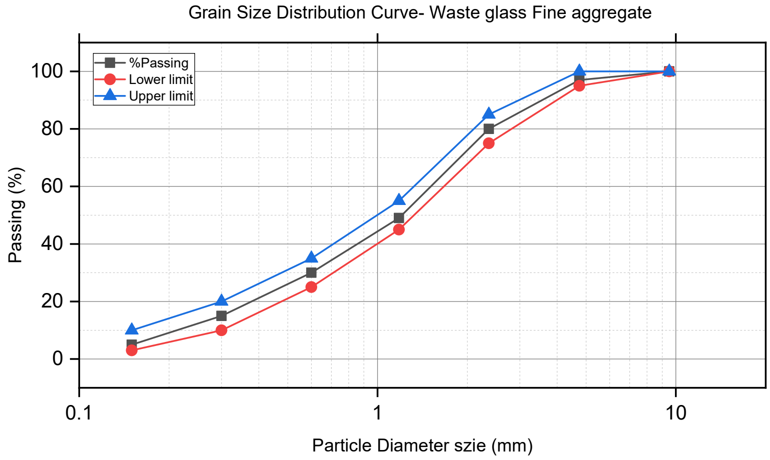

Figure 6. Grain size distribution curve of fine waste glass.

2.5. Mix Designing and Proportioning

The material properties (cement, aggregate, shredded plastics, and waste glass) and concrete characteristics containing the waste glass and plastic were examined. In addition, the mathematical approach to the volume-based analysis of materials was considered for the concrete mix production to evaluate the physical and mechanical properties (workability, compressive strength, flexural strength, and splitting tensile strength).

The appropriate quantities of cement, sand, aggregates, waste plastics, and glass were used to create a concrete mix. The main purpose here was to find the optimum replacement of waste plastics and glass that could be utilized to manufacture concrete that meets the performance standards of concrete under loads and in diverse environments.

2.5.1. Mix Design for Waste Plastics to Glass

Different trial mixes were proportioned by observing concrete's workability and compressive strength to obtain the appropriate waste plastic and glass ratio. As a result, the optimum ratio of WP to WG was determined. Table 4 summarizes the mix properties of the concrete mix without any waste glass and plastics content for three various water–cement ratios. These ratios cover the most widely applicable engineering practices, from 0.4 to 0.6. The mixes conform to the standards and specifications of ASTM C136 [51] and ASTM C 33-03 [52]. Finally, the mix proportion for the C-25 concrete grade is tabulated in Table 5 with different water–cement ratios.

Table 4. Mix proportioning for one m^3 of concrete.

Type of Mix	w/c	Cement (kg/m^3)	Water (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	Plastic Waste (kg/m^3)	Glass Waste (kg/m^3)
Control	0.4	475	165	768	1007	0.0	0.0
Control	0.5	380	162	850	1007	0.0	0.0
Control	0.6	316.67	160	905	1007	0.0	0.0

Table 5. Design of concrete mixtures and number of test specimens for compressive strength at each test age.

Group No	w/c Ratio	% of WP and WG	WP: WG Ratio	Number of Compressive Strength Tests	
				7th Day	28th Day
WPG-0	0.4	0	0:0	3	3
WPG-1		10	3:7	3	3
WPG-2		20	6:14	3	3
WPG-3		30	10:20	3	3
WPG-0	0.5	0	0:0	3	3
WPG-1		10	3:7	3	3
WPG-2		20	6:14	3	3
WPG-3		30	10:20	3	3
WPG-0	0.6	0	0:0	3	3
WPG-1		10	3:7	3	3
WPG-2		20	6:14	3	3
WPG-3		30	10:20	3	3

With different controlling factors, such as water–cement ratio, waste plastics, and glass proportions, four mixes and 72 standard compressive sample specimens were used in the experiments. For comparison purposes, the reference testing samples were plain concrete with no WG and WP content. Table 5 summarizes the complete experimental plan.

2.5.2. Mix Design for Fine Aggregate, Waste Plastic, and Glass

The testing program continued focusing only on the two mixes with optimal output results, i.e., sample WPG-0 at a water–cement ratio of 0.4 and 20% of the fine aggregate replaced by WG and WP. We used a w/c ratio of 0.40 because the concrete workability was stable compared to the control mixture. However, the workability and strength of the concrete are affected when using a w/c ratio above 0.50. Based on these results, an extra series of 12 tests were conducted to determine the flexural strength and the splitting resistance of the two optimal concrete mixes. The trial mix for WP and WG using a water–cement ratio of 0.4 is described in Table 6.

Table 6. Trial mix for waste plastic and glass ratio for water–cement ratio of 0.4.

Type of Mix	Mix Ratio of WP to WG	Cement (kg/m^3)	Water (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	Plastic Waste (kg/m^3)	Glass Waste (kg/m^3)
Control (WPG-0)	N/A	38.475	13.65	62.20	81.57	0.00	0.0
WPG-1	1:1	38.475	13.65	49.76	81.57	6.22	6.22
WPG-2	1:1.5	38.475	13.65	49.7664	81.57	4.976	7.46
WPG-3	1:2	38.475	13.65	49.76	81.57	4.15	8.29
WPG-4	1:2.5	38.475	13.65	49.76	81.57	3.55	8.88
WPG-5	1:3	38.475	13.65	49.76	81.57	3.11	9.33

The mix proportions for compressive strength at the 7th and 28th days with different water–cement ratio are summarized in Table 7.

Table 7. Mix proportions for 0.081 m^3 of concrete.

Type of Mix	w/c	Cement (kg/m^3)	Water (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	Plastic Agg (kg/m^3)	Glass Agg (kg/m^3)
Plain (PG-0)	0.4	38.475	13.65	62.20	81.57	0.00	0.0
WPG-1	0.4	38.475	13.65	55.9872	81.57	2.0736	4.1472
WPG-2	0.4	38.475	13.65	49.7664	81.57	4.1472	8.2944
WPG-3	0.4	38.475	13.65	43.5456	81.57	6.2208	12.4416
Plain (PG-0)	0.5	30.78	13.12	68.85	81.57	0.0	0.0
WPG-1	0.5	30.78	13.12	61.965	81.57	2.295	4.59
WPG-2	0.5	30.78	13.12	55.08	81.57	4.59	9.18
WPG-3	0.5	30.78	13.12	48.195	81.57	6.885	13.77
Plain (XPG-0)	0.6	32.7	25.65	73.305	81.57	0.0	0.0
WPG-1	0.6	32.7	25.65	65.9745	81.57	2.4435	4.887
WPG-2	0.6	32.7	25.65	58.644	81.57	4.887	9.774
WPG-3	0.6	32.7	25.65	51.3135	81.57	7.3305	14.661

2.6. Concrete Specimens Preparation

Initially, a certain amount of water was added to the aggregates and left for a short while to bring the aggregates to the saturated surface dry condition (SSD). Next, the fine aggregate, coarse aggregate, and cement were dry mixed for about a minute. Next, the fine glass and plastic wastes were carefully added to the dry mix to avoid segregation, followed by the addition of two-thirds of the total mixing water.

Twelve 150 mm cubes, three 150 × 300 mm cylinders, and three 100 × 100 × 500 mm beams were cast for each mix. Cubes were used to measure the compressive strength on the 7th and 28th days. In addition, the 28th day's tensile strength and flexural tensile strength were evaluated using cylinder specimens and beam specimens, as shown in Figure 7.

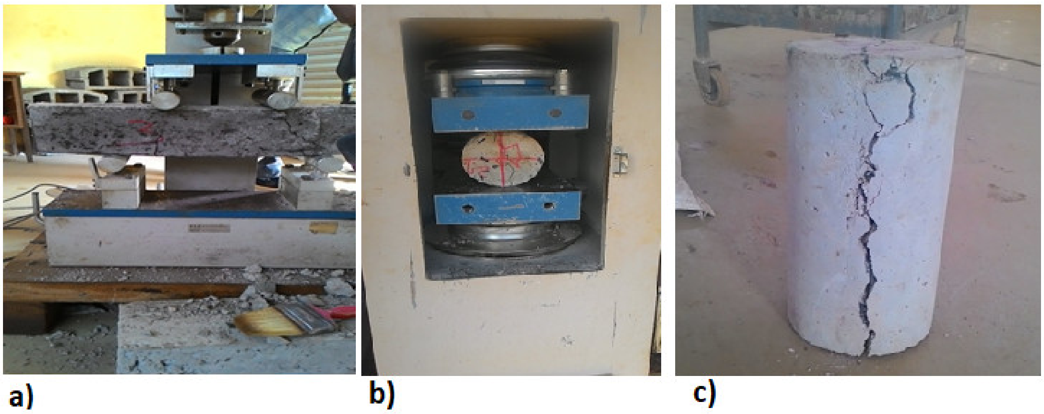

Figure 7. Sample under test: (**a**) flexural strength, (**b**) tensile strength, (**c**) failure under tensile test.

3. Results and Discussions

3.1. The Test Program for Concrete Mix Design

For the laboratory procedures, the concrete grade C-25 compressive strength was used to understand the effect of compressive strength.

The ratios of plastics to glass in the mix were determined by using the estimated quantity of waste with a water-to-cement ratio of 0.4 and observing the effect on the compressive strength of the concrete on the 7th day (Table 8).

Table 8. Compressive strength of concrete at 7 days for varying ratios of waste plastics to waste glass (WP:WG).

Group Number	WP:WG	-	7th-Day Compressive Strength (MPa)
(Control)	0:0	Mean Standard deviation	20.6 0.20
M2-PG-2	1:1.5	Mean Standard deviation	16.2 0.30
M2-PG-2	1:1.5	Mean Standard deviation	19.27 0.152
M4-PG-4	1:2.5	Mean Standard deviation	20.46 0.155
M5-PG-5	1:3	Mean Standard deviation	20.8 0.10

As shown in Table 8, the compressive strength increases as the ratio of plastics in the mix decreases and the glass increases. It shows that the added glass has positive effect by improving the compressive strength of the concrete, compared with the waste plastic.

The mean concrete compressive strength on the 7th day for the ratio of WP to WG (1:1, 1:1.5, 1:2, 1:2.5 and 1:3) was compared with the control mix concrete's compressive strength. From the proportions of the plastics to glass, a ratio of 1:2 was selected because in the first two ratios the compressive strength decreased, while in the 1:2.5 ratio and 1:3 ratio, the amount of glass was high and amount of plastic was low, but the strength met the standard. However, these ratios were not selected since the quantity of glass in the mix was significantly higher than the combined plastic quantity.

When the ratios of plastic to glass were 1:2, 1:2.5, and 1:3, the mean compressive strength of the concrete was almost equal with the control mix, as shown in Table 8. Thus, for practical purposes in terms of the proportions of the plastics to glass, a ratio of 1:2I was selected due to the fact that the volume of the plastic waste is much greater than that of glass wastes in the study area of this research. However, from a scientific point of view, a ratio of 1:3 is recommended since the maximum compressive strength was observed at this mix ratio.

Thus, it is inferred that the replacement of sand with plastic waste up to 15% can be adopted so that the disposal of used plastic can be reduced and the lack of natural aggregates can be managed effectively [53].

When 30% of the fine aggregate was replaced by waste glass, the strength was only about 1% lower than that of the control, which is a promising result [35]. Therefore, the 1:2 ratio was selected as the optimum ratio of plastics to glass in the mix during the investigation.

3.2. Effect of Waste Plastics and Glass on the Workability of Concrete

As shown in Table 9, the fresh concrete workability was inversely affected by the increase in water–cement ratio and decreased as the percentage of fine WP and WG was increased.

Table 9. Slump test results.

Grade	w/c	Sample	Slump Test (mm)	Grade	w/c	Sample	Slump Test (mm)	Grade	w/c	Sample	Slump Test (mm)
C-25	0.4	PG-0	10	C-25	0.5	PG-0	95	C-25	0.6	PG-0	240
	0.4	PG-1	9.5		0.5	PG-1	90		0.6	PG-1	230
	0.4	PG-2	7		0.5	PG-2	80		0.6	PG-2	220
	0.4	PG-3	7		0.5	PG-3	30		0.6	PG-3	210

Clearly, fine WP and WG in concrete significantly decreased the workability. Specifically, for a w/c ratio of 0.4 replacing 10% of the fine aggregate with fine WP and WG, the change was negligible. However, it significantly decreased the workability for a w/c ratio of 0.5 and above the fine WP and WG introduced to the concrete.

Generally, the water to cement ratio affected the concrete workability, rather than the introduction of waste plastics and glass to the mix. The slump tests with and without the wastes are shown in Figure 8.

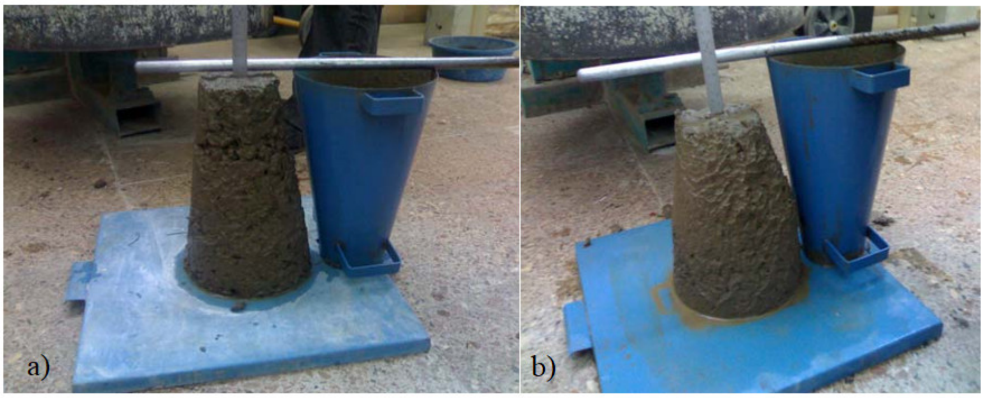

Figure 8. Example of slump test (**a**) for plain concrete and (**b**) for waste plastic and glass.

3.3. Unit Weight Test Results

The results for different sample groups regarding the unit weight for hardened concrete are listed in Table 10.

Table 10. Unit weight of concrete with series of proportions of fine waste plastics and glass contents.

Specimen	w/c	Waste (%)	WP:WG	Unit wt. (g/cm^3)	Reduction (%)
WPG-0	0.4	0	0	2.35	0.00
WPG-1	0.4	10	3:7	2.39	1.70
WPG-2	0.4	20	6:14	2.33	0.85
WPG-3	0.4	30	10:20	2.37	0.85
WPG-0	0.5	0	0	2.36	0.00
WPG-1	0.5	10	3:7	2.49	5.5
WPG-2	0.5	20	6:14	2.24	5.08
WPG-3	0.5	30	10:20	2.29	2.97
WPG-0	0.6	0	0	2.19	0.00
WPG-1	0.6	10	3:7	2.05	6.40
WPG-2	0.6	20	6:14	2.01	8.22
WPG-3	0.6	30	10:20	2.0	8.67

It was shown that the concrete unit weight decreased as the water–cement ratio increased. For example, at a water–cement ratio of 0.4, the maximum reduction was 1.7%; at a water–cement ratio of 0.5, the maximum reduction in unit weight was 5.5%; and at a water–cement ratio of 0.6, the maximum reduction was 8.67%. According to ASTM C 33, the concrete unit weight at w/c = 0.4 fulfills the requirements of normal weight concrete: it must be between 2.2 and 2.4 (g/cm^3). Therefore, a water–cement ratio of 0.4 was selected for the investigation since the percentage of reduction in unit weight was minimal.

3.4. Effect of Waste Plastics and Glass on Compressive Strength of Concrete

As shown in Table 11, at water–cement ratios of 0.4 and 10% WP and WG, the compressive strength at 7 and 28 days was increased by 12.55% and 6.44%, respectively. Nevertheless, at w/c = 0.5 and 0.6 and all introductions of WP to WG, the compressive strength at 7 and 28 days was decreased. On the other hand, at 20% replacement, a reduction was observed by 14.35% and 0.73% on the 7th and 28th day, respectively. In this case, the concrete designs for C-25, on the 28th day, the compressive strength was 26.9 MPa. Therefore, if the impact of the WG and WP on the environment was considered a primary issue, it is possible to use up to 20% replacement for fine aggregate for simple structures where lightweight concrete is required.

Table 11. The 7- and 28-day compressive strengths of concrete with several fine waste plastic to glass contents at different water–cement ratios.

Samples	w/c	WP and WG (%)	WP:WG	Compressive Strength (MPa)		Strength Change (%)	
				7 Days	28 Days	7 Days	28 Days
WPG-0	0.4	0	0	22.3	27.1	0.00	0.00
WPG-1		10	3:7	25.1	28.9	+12.55	+6.64
WPG-2		20	6:14	19.1	26.9	−14.35	−0.73
WPG-3		30	10:20	15.0	25.4	−32.74	−6.27
WPG-0	0.5	0	0	20.7	27.3	0.00	0.00
WPG-1		10	3:7	19.1	26.8	−7.73	−1.83
WPG-2		20	6:14	18.3	25.2	−11.59	−7.70
WPG-3		30	10:20	16.8	25.0	−18.84	−8.82
WPG-0	0.6	0	0	20.5	27.0	0.00	0.00
WPG-1		10	3:7	15.5	22.5	−24.39	−16.67
WPG-2		20	6:14	16.2	21.5	−20.97	−20.37
WPG-3		30	10:20	14.3	19.2	−30.92	−28.89

A summary of the effect of the water–cement ratio on compressive strength is shown in Figure 9. It can be observed that the compressive strength decreases as the water–cement ratio increases across all tested percentages of waste materials used as fine aggregate replacements.

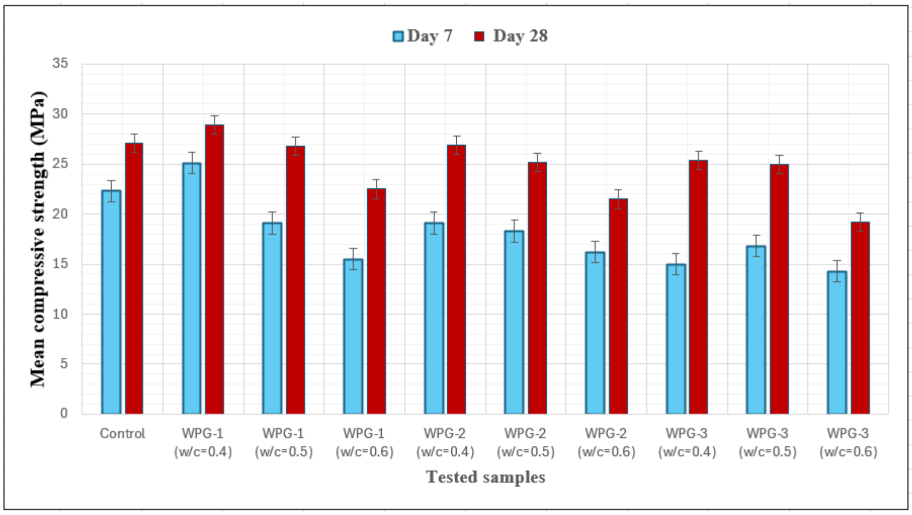

Figure 9. Compressive strength at different percentages of waste materials and various water–cement ratios.

3.5. Optimal Waste Plastic and Glass Contents in Concrete Mixes

As shown in Table 12, the optimum compressive strength was obtained with a 10% replacement of fine aggregate by WG and WP. However, as discussed earlier, utilizing a 20% replacement is also feasible, as the mean compressive strength on the 28th day remains sufficient. This approach will help increase the percentage of waste materials being recycled.

Table 12. The 7- and 28-day compressive strength of concrete at w/c = 0.4.

Group No.	WP and WG (%)	7-Days Compressive Strength (MPa)	28-Days Compressive Strength (MPa)
WPG-0	0	22.3	27.1
WPG-1	10	25.1	28.9
WPG-2	20	19.1	24.9
WPG-3	30	15.0	24.4

3.6. Effect of Waste Plastic and Glass on Flexural Strength

The prepared beam samples were tested after 28 days of standard curing, and the results of the flexural strength tests for the control concrete and the waste plastics and glass concretes are illustrated in Figure 9. The bending strength of the concrete (σ) in MPa was obtained based on Equation (1).

$$\sigma = \frac{MC}{I} \tag{1}$$

where σ—bending strength, M—maximum moment, I—moment of inertia, and C—centroid depth.

The results demonstrate the effect of fine waste plastic (WP) and waste glass (WG) contents in concrete mixes on the flexural strength of the concrete. As illustrated in Figure 10, when 20% of the fine aggregate is replaced by WG and WP, the flexural strength increases by 19.7%, from 12.46 MPa to 15.52 MPa.

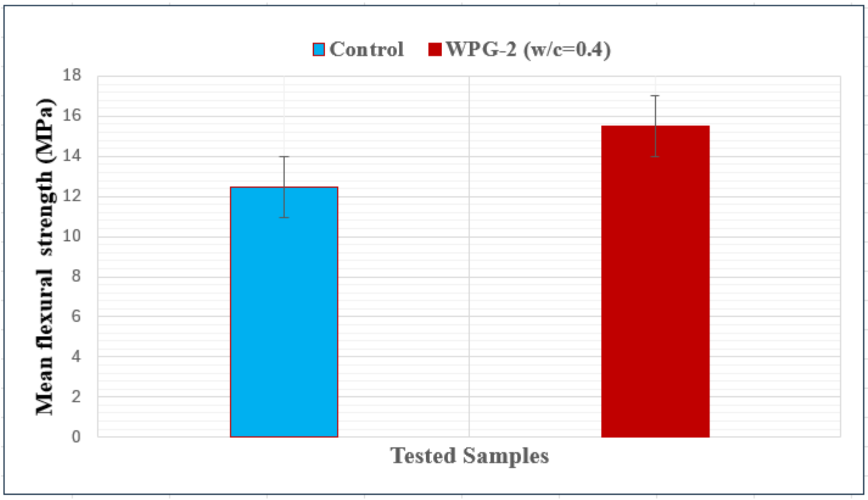

Figure 10. Example of mean flexural strength of C-25 concretes on day 28 with a water–cement ratio of 0.4.

This significant improvement in flexural strength suggests that incorporating WG and WP as partial replacements for traditional fine aggregates can enhance the mechanical properties of concrete. The increase in flexural strength can be attributed to the improved bonding and distribution of stress within the concrete matrix provided by the WG particles. In contrast, the presence of WP might contribute to a lesser extent, indicating that WG has a more pronounced effect on the flexural performance. These findings highlight the potential of utilizing waste materials in concrete production, promoting sustainable construction practices while enhancing material properties.

3.7. Effect of Waste Plastics and Glass on Splitting Tensile Strength

The results show that the use of optimal fine aggregate WP and WG contents in the concrete mix reduced the splitting tensile strength of the mixture slightly.

Equation (2) gives the horizontal stress to which the element is subjected.

$$\sigma_t = \frac{2P}{\pi LD} \tag{2}$$

where P—the applied compressive load, L—the cylinder length, and D—the cylinder diameter.

The split tensile strength of the control mix was 4.65 MPa, and the inclusion of waste plastics and glass into the concrete resulted in a 4.3 MPa splitting tensile strength on the 28th day of curing, as shown in Figure 11. Therefore, the introduction of WP and WG slightly decreased the splitting tensile strength compared to a plain concrete mix. The study conducted in [54] concludes that concrete mortar could be made completely sustainable by using recycled materials like glass, plastic, and recycled concrete, as well as micro-silica and fly ash, and that only 20% of the weight of cement could be used without lowering the compressive and flexural strength of the concrete.

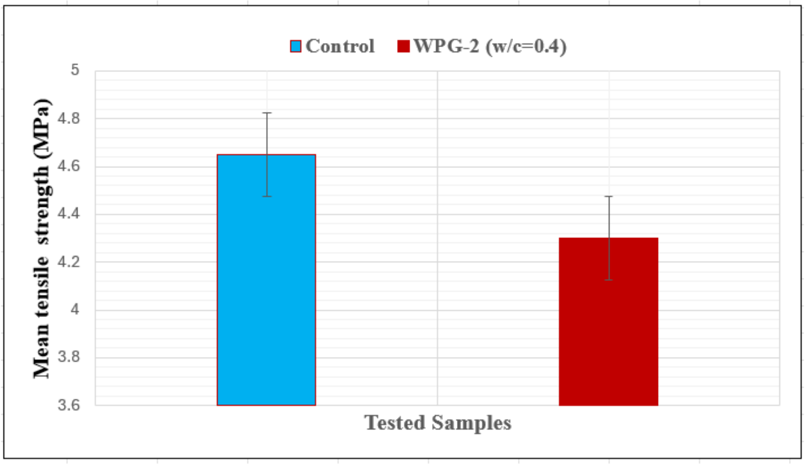

Figure 11. Example of tensile strength of C-25 concretes on day 28 with a water–cement ratio of 0.4.

4. Conclusions

The experimental study on concrete samples incorporating plastic and glass wastes as partial replacements for fine aggregate yielded the following key findings. Based on these findings, the following conclusions can be drawn:

The optimal mix ratio of plastics to glass waste was determined to be 1:2.3. This ratio was found to provide the best balance between the structural integrity and recyclability of the resulting material. Using this specific proportion ensures that the composite material benefits from the desirable properties of both plastic and glass, making it suitable for various practical applications.

Incorporating waste plastics and glass into the concrete mix slightly reduced the workability at water–cement ratios of 0.5 and 0.6. However, the workability remained unaffected when the water–cement ratio was 0.4. Therefore, a water–cement ratio of 0.4 is recommended to produce sustainable concrete from waste plastics and glass.

The investigation determined that the optimal replacement of fine aggregate with waste materials was 10%, comprising 7% waste glass and 3% waste plastic. However, to effectively utilize the waste materials, a 20% replacement—comprising 14% waste glass and 6% waste plastic—is a better option, as the mean compressive strength is almost

25 MPa. This finding highlights a balanced approach to enhancing the sustainability of concrete production.

The compressive strength of concrete increases as the proportion of plastics in the mix decreases and the amount of glass increases. This indicates that glass exerts a more significant influence on the compressive strength compared to plastics.

In concrete mixes containing the optimal proportion of fine waste plastics and glass, there was a significant enhancement observed in the flexural strength. However, there was a slight decrease noted in the splitting tensile strength.

Overall, these findings highlight the potential for sustainable construction practices by effectively integrating waste materials into concrete production processes.

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References

1. Meddah, M.S. Use of waste window glass as substitute of natural sand in concrete production. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *603*, 032011. [CrossRef]
2. Muda, M.M.; Legese, A.M.; Urgessa, G.; Boja, T. Strength, Porosity and Permeability Properties of Porous Concrete Made from Recycled Concrete Aggregates. *Constr. Mater.* **2023**, *3*, 81–92. [CrossRef]
3. Legese, A.M.; Kenate, T.G.; Feyessa, F.F. Termite Mound Soils for Sustainable Production of Bricks. *Stud. Geotech. Mech.* **2021**, *43*, 142–154. [CrossRef]
4. Abegaz, G.T.; Khan, I.; Legese, A.M. Investigating the Effects of Coarse Aggregate Physical Properties on Strength of C-25 Concrete. *Am. J. Eng. Technol. Manag.* **2020**, *5*, 84–90. [CrossRef]
5. Tsega, E.; Mosisa, A.; Fufa, F. Effects of Firing Time and Temperature on Physical Properties of Fired Clay Bricks. *Am. J. Civ. Eng.* **2017**, *5*, 21. [CrossRef]
6. Etefa, G.; Mosisa, A. Waste Rubber Tires: A Partial Replacement for Coarse Aggregate in Concrete Floor Tile Production. *Am. J. Civ. Eng.* **2020**, *8*, 57–63. [CrossRef]
7. Getachew, K.; Mosisa, A. Laboratory Investigation of Locally Produced Clay Brick Quality and Suitability for Load Bearing Element in Jimma Area, Ethiopia. *Int. J. Eng. Res. Technol.* **2017**, *6*, 809–817.
8. Statista. Global Plastic Waste Volume 1950–2050. *Statista*. 2021. Available online: https://www.statista.com/statistics/1019774/plastic-waste-volume-globally/ (accessed on 31 March 2022).
9. Dinku, A. The need for standardization of aggregates for concrete production in Ethiopian construction industry. In Proceedings of the Third International Conference on Development Studies in Ethiopia, Addis Ababa, Ethiopia, 18–19 June 2005; pp. 1–15.
10. Mayer, M. Recycling Potential of Construction Materials: A Comparative Approach. *Constr. Mater.* **2024**, *4*, 238–250. [CrossRef]
11. Agyeman, S.; Obeng-Ahenkora, N.; Assiamah, S.; Twumasi, G. Exploiting recycled plastic waste as an alternative binder for paving blocks production. *Case Stud. Constr. Mater.* **2019**, *11*, e00246. [CrossRef]
12. Liebenberg, C.J. Waste recycling in developing countries in Africa: Barriers to improving reclamation rates. In Proceedings of the Eleventh International Waste Management and Landfill Symposium, Cagliari, Italy, 1–5 October 2007; pp. 1–5.
13. Miller, S.A.; Habert, G.; Myers, R.J.; Harvey, J.T. Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. *One Earth* **2021**, *4*, 1398–1411. [CrossRef]
14. Latawiec, R.; Woyciechowski, P.; Kowalski, K.J. Sustainable Concrete Performance—CO_2-Emission. *Environments* **2018**, *5*, 27. [CrossRef]
15. Burgmann, S.; Breit, W. Impact of Crushed Natural and Recycled Fine Aggregates on Fresh and Hardened Mortar Properties. *Constr. Mater.* **2023**, *4*, 37–57. [CrossRef]
16. Valderrama, D.M.A.; Cuaspud, J.A.G.; Taniolo, N.; Boccaccini, A.R. Glass-Ceramic Materials Obtained by Sintering of Vitreous Powders from Industrial Waste: Production and Properties. *Constr. Mater.* **2021**, *1*, 63–79. [CrossRef]
17. Wang, T.; Nicolas, R.S.; Kashani, A.; Ngo, T. Sustainable utilisation of low-grade and contaminated waste glass fines as a partial sand replacement in structural concrete. *Case Stud. Constr. Mater.* **2022**, *16*, e00794. [CrossRef]
18. Thiam, M.; Fall, M.; Diarra, M. Mechanical properties of a mortar with melted plastic waste as the only binder: Influence of material composition and curing regime, and application in Bamako. *Case Stud. Constr. Mater.* **2021**, *15*, e00634. [CrossRef]

19. Saikia, N.; de Brito, J. Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. *Constr. Build. Mater.* **2012**, *34*, 385–401. [CrossRef]
20. Merlo, A.; Lavagna, L.; Suarez-Riera, D.; Pavese, M. Mechanical properties of mortar containing waste plastic (PVC) as aggregate partial replacement. *Case Stud. Constr. Mater.* **2020**, *13*, e00467. [CrossRef]
21. Aocharoen, Y.; Chotickai, P. Compressive mechanical properties of cement mortar containing recycled high-density polyethylene aggregates: Stress–strain relationship. *Case Stud. Constr. Mater.* **2021**, *15*, e00752. [CrossRef]
22. Kane, S.; Thane, A.; Espinal, M.; Lunday, K.; Armağan, H.; Phillips, A.; Heveran, C.; Ryan, C. Biomineralization of Plastic Waste to Improve the Strength of Plastic-Reinforced Cement Mortar. *Materials* **2021**, *14*, 1949. [CrossRef]
23. Awoyera, P.O.; Olalusi, O.B.; Ibia, S.; Prakash, A.P. Water absorption, strength and microscale properties of interlocking concrete blocks made with plastic fibre and ceramic aggregates. *Case Stud. Constr. Mater.* **2021**, *15*, e00677. [CrossRef]
24. Bahij, S.; Omary, S.; Feugeas, F.; Faqiri, A. Fresh and hardened properties of concrete containing different forms of plastic waste—A review. *Waste Manag.* **2020**, *113*, 157–175. [CrossRef]
25. Almeshal, I.; Tayeh, B.A.; Alyousef, R.; Alabduljabbar, H.; Mohamed, A.M. Eco-friendly concrete containing recycled plastic as partial replacement for sand. *J. Mater. Res. Technol.* **2020**, *9*, 4631–4643. [CrossRef]
26. Al-Luhybi, A.S.; Qader, D.N. Mechanical Properties of Concrete with Recycled Plastic Waste. *Civ. Environ. Eng.* **2021**, *17*, 629–643. [CrossRef]
27. Sharifi, Y.; Houshiar, M.; Aghebati, B. Recycled glass replacement as fine aggregate in self-compacting concrete. *Front. Struct. Civ. Eng.* **2013**, *7*, 419–428. [CrossRef]
28. Rashad, A.M. Recycled waste glass as fine aggregate replacement in cementitious materials based on Portland cement. *Constr. Build. Mater.* **2014**, *72*, 340–357. [CrossRef]
29. Yan, L.L.; Liang, J.F. Use of waste glass as coarse aggregate in concrete: Mechanical properties. *Adv. Concr. Constr.* **2019**, *8*, 1–7. [CrossRef]
30. Ahmad, J.; Martínez-García, R.; De-Prado-Gil, J.; Irshad, K.; El-Shorbagy, M.A.; Fediuk, R.; Vatin, N.I. Concrete with Partial Substitution of Waste Glass and Recycled Concrete Aggregate. *Materials* **2022**, *15*, 430. [CrossRef]
31. Ashiq, S.Z.; Akbar, A.; Farooq, K.; Mujtaba, H. Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive. *Case Stud. Constr. Mater.* **2022**, *16*, e00883. [CrossRef]
32. Ibrahim, K.I.M. Recycled waste glass powder as a partial replacement of cement in concrete containing silica fume and fly ash. *Case Stud. Constr. Mater.* **2021**, *15*, e00630. [CrossRef]
33. Nassar, R.-U.; Soroushian, P.; Sufyan-Ud-Din, M. Long-term field performance of concrete produced with powder waste glass as partial replacement of cement. *Case Stud. Constr. Mater.* **2021**, *15*, e00745. [CrossRef]
34. He, Z.H.; Yang, Y.; Zeng, H.; Chang, J.Y.; Shi, J.Y.; Liu, B.J. Waste glass powder and its effect on the fresh and mechanical properties of concrete: A state of the art review. *Adv. Concr. Constr.* **2020**, *10*, 417–429. [CrossRef]
35. Islam, G.M.S.; Rahman, M.H.; Kazi, N. Waste glass powder as partial replacement of cement for sustainable concrete practice. *Int. J. Sustain. Built Environ.* **2017**, *6*, 37–44. [CrossRef]
36. Małek, M.; Łasica, W.; Jackowski, M.; Kadela, M. Effect of waste glass addition as a replacement for fine aggregate on properties of mortar. *Materials* **2020**, *13*, 3189. [CrossRef]
37. Team, W. *Pollution Caused by Solid Waste, Rubble, and Construction Debris Is a Serious Threat to the Sea and the Shore of the Gaza Strip*; United Nations Office for the Coordination of Humanitarian Affairs (OCHA): Gaza Strip, Palestine, 2009.
38. Babu, K.G.; Babu, D.S. Behaviour of lightweight expanded polystyrene concrete containing silica fume. *Cem. Concr. Res.* **2003**, *33*, 755–762. [CrossRef]
39. Olofinnade, O.; Morawo, A.; Okedairo, O.; Kim, B. Solid waste management in developing countries: Reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production. *Case Stud. Constr. Mater.* **2021**, *14*, e00532. [CrossRef]
40. Bjerkli, C.L. *The Cycle of Plastic Waste: An Analysis on the Informal Plastic Recovery System in Addis Ababa, Ethiopia*; Geografisk Institutt: Trondheim, Norway, 2005.
41. Shi, C.; Zheng, K. A review on the use of waste glasses in the production of cement and concrete. *Resour. Conserv. Recycl.* **2007**, *52*, 234–247. [CrossRef]
42. Topçu, İ.B.; Canbaz, M. Properties of concrete containing waste glass. *Cem. Concr. Res.* **2004**, *34*, 267–274. [CrossRef]
43. Dhanani MG, V.; Bhimani MP, D. Effect of Use Plastic Aggregates as partial replacement of natural aggregates in concrete with plastic fibres. *Int. Res. J. Eng. Technol.* **2016**, *3*, 2569–2573.
44. KBabu, G.; Babu, D.S. Performance of fly ash concretes containing lightweight EPS aggregates. *Cem. Concr. Compos.* **2004**, *26*, 605–611. [CrossRef]
45. Osei, D.Y. Experimental investigation on recycled plastics as aggregate in concrete. *Int. J. Struct. Civ. Eng. Res.* **2014**, *3*, 168–174.
46. Premalatha, J.; Ahmed, S.A. Experimental study on concrete with plastic aggregates. *SSRG Int. J. Civ. Eng.* **2017**, 358–363.
47. Mathew, P.; Varghese, S.; Paul, T.; Varghese, E. Recycled plastics as coarse aggregate for structural concrete. *Int. J. Innov. Res. Sci. Eng. Technol.* **2013**, *2*, 687–690.
48. Tamang, L.W.T.; Wangmo, T.; Darjay, K.T.; Phuntsho, K.S.; Namgyal, P.; Wangchuk, U. Use of plastics in concrete as coarse aggregate. *Int. J. Educ. Appl. Res.* **2017**, *7*, 9–13.
49. Dinku, A. *Construction Materials Laboratory Manual*; Addis Ababa University Press: Addis Ababa, Ethiopia, 2002.

50. Cement, A.P. ASTM C 150, Type I or II, except Type III may be used for cold-weather construction. *Provid. Nat. Color Or White Cem. Required Prod. Mortar Color Indic.* **1993**, *1*.
51. *ASTM C136-06*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM: West Conshohocken, PA, USA, 2005; Volume 13, pp. 85–86.
52. *ASTM C33*; Standard Specifications for Concrete Aggregates. ASTM: West Conshohocken, PA, USA, 2001; Volume 4.
53. Mindess, S.; Young, F.J.; Darwin, D. *Concrete*, 2nd ed.; Prentice Hall, Pearson Education: Hoboken, NJ, USA, 2003.
54. Najaf, E.; Abbasi, H. Using recycled concrete powder, waste glass powder, and plastic powder to improve the mechanical properties of compacted concrete: Cement elimination approach. *Adv. Civ. Eng.* **2022**, *2022*, 9481466. [CrossRef]