The Effectiveness of Recycled Glass Powder in Improving the Properties of Fibrous Mortar

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ABSTRACT

Sustainability has become one of the most important topics at present, being applied in all aspects of life, including the production of sustainable building materials by integrating various wastes into different forms, such as fibers or powder, to enhance the properties of concrete or mortar. In this work, three types of waste were used: glass waste as powder and a partial substitute for cement, eggshells having served as a partial substitute for cement, and finally, soft drink cans were cut and utilized as fibers. A 15% glass powder was utilized with varying percentages of fiber. Fiber improves tensile strength and reduces concrete spalling; however, the fibers derived from waste have limited bond strength with the mortar. The use of pozzolanic materials (glass powder) has enhanced bond strength, thereby improving multiple properties of concrete. Aluminum fibers were added in amounts of 0.25%, 0.5%, 0.75%, and 1%. The lowest compressive strength was observed in the mixture containing 1% fiber, without any cement replacement with pozzolanic materials. The best results were achieved with the mixture containing 0.5% fiber and 15% glass powder, particularly in terms of flexibility and impact resistance.

Keywords-aluminum fibers; flexural strength; glass powder; UPV; impact

I. INTRODUCTION

Concrete enhancement studies have been a primary goal, especially at present. The major purpose of concrete improvement studies is to address or reduce pollution caused by the cement industry. Furthermore, the accumulation of industrial waste puts pressure on academia to develop more sustainable and environmentally friendly construction materials by enhancing concrete's brittleness and ductility. As a result, concrete performance has been improved using polypropylene fiber [1], steel fiber [2], aluminum fiber [3], etc. Fiber addition increases numerous technical properties of concrete, mortar, and cement paste, including fracture toughness, flexural strength, fatigue resistance, impact, thermal shock, and splitting [4]. Authors in [5] discovered that the optimal amount of aluminum fibers added to lightweight concrete is 15% by volume fraction. Concrete containing 1% and 2% aluminum fibers from soft drink cans was evaluated for compressive and flexural strength in addition to a reference concrete. Fiber concrete outperformed the reference concrete in terms of compressive and flexural strength, with 1% soft drink can performing better than 2% [6]. Authors in [7] studied the mechanical characteristics of aluminum fibers obtained by cutting trash soft drink cans. They employed small fiber content values of 0.1%, 0.2%, 0.3%, and 0.4%. The results indicated a decrease in slump and concrete absorption. Mechanical characteristics, including compressive, splitting, and flexural strengths, improved with 0.3% fiber inclusion. Large amounts of greenhouse gases are released during the manufacture of concrete, primarily from cement. About 870 kg of CO_2 are produced for every ton of Portland cement, with 5% of the world's CO_2 emissions emerging from the manufacture of cement [8]. The use of waste in concrete is currently a global trend for effective waste management, considering a sustainable green environment along with the additional advantages of conserving natural resources and creating more effective materials. The accumulation of waste poses risks to the environment, creates other problems and hazards, and requires time and money to remove and dispose of it in designated areas. To address this issue, researchers have recently shown that waste glass may be used in concrete as a partial substitute for cement [9]. Glass is a brittle consumer material that can be fully recycled without losing its uniformity, regardless of its shape, size, or form—such as bottles, windows, and other applications [10]. Numerous studies have shown that replacing part of the cement in concrete with ground waste glass powder enhances its properties [11]. The pozzolanic activity of glass powder has been evaluated in various studies. The results indicate that, in addition to improving other properties by up to 15%, the average compressive strength of concrete containing glass powder has increased by 16% [12]. However, as the glass content increases, the splitting tensile strength tends to decrease. Other findings demonstrate that using up to 20% glass powder can result in concrete with moderate strength, suitable for sustainable structural applications [13]. Authors in [14] identified 10% glass powder combined with nano clay as the optimal level, beyond which the concrete's quality significantly declines. Additionally, studies, such as [15], confirm that glass powder can partially replace cement in self-compacting concrete. Although fibers offer several advantages when added to concrete, the bond between the fiber surface and the cement paste is often weak, especially when waste fibers are used. This weak bond reduces the effectiveness of the fibers. Combining aluminum fibers with glass powder may provide improved results. Notably, previous research has primarily examined either glass powder or aluminum fibers individually; no prior studies have evaluated their combined effect in concrete.

II. EXPERIMENTAL PROGRAM (MATERIALS, MIX PROPORTIONS, SLAB FABRICATION, AND TESTS)

In accordance with [16], Type Cem I cement with a Specific Gravity (SG) of 3.15 was used in this study. The fine aggregate had a maximum particle size of 4.25 mm and an SG of 2.58, both meeting the requirements of [17]. The sand used had an absorption rate of 0.16% and an SO_3 content of 0.15%, which also fell within the limits specified in [17]. Potable water was utilized for both mixing and curing. A Type F and D superplasticizer was added to improve workability without altering the water-to-cement (w/c) ratio, complying with [18]. Waste glass bottles from juices and soft drinks were collected to produce Powder of Waste Glass (POWG). The glass was first crushed into fine aggregates, then ground into a fine powder and sieved through a No. 200 mesh, as shown in Figure 1. The chemical composition of the resulting POWG is presented in Table I. POWG acted as a pozzolanic material in this study and met the standards of [19] based on its Pozzolanic Activity Index (PAI), which was measured at 95.28 at 28 days—complying with the acceptable criteria. Additionally, aluminum cans from soft drinks were collected and processed. The top and bottom sections of the cans were removed to form flat sheets, which were then cut into rectangular aluminum fibers measuring 30 mm in length, 3 mm in width, and 0.25 mm in thickness, as illustrated in Figure 2. These fibers were added to the mortar mixes at volume fractions of 0.25%, 0.5%, 0.75%, and 1%. All mixes used the same base composition: 350 kg/m³ of cement, 1050 kg/m³ of sand, a w/c ratio of 0.38, and 1.25% superplasticizer. The mix proportions are detailed in Table II.

TABLE I. MAIN CHEMICAL COMPOSITION OF CEMENT AND POWG

Oxide composition	Cement	POWG
CaO	66.8	2.06
SiO_2	22.08	89.85
Al_2O_3	5.50	0.78
Fe_2O_3	3.37	0.204

The workability of the mixes was assessed using the flow table test by [20]. Cube specimens of 50 mm × 50 mm × 50 mm were utilized and evaluated using a standard compression machine with a 2000kN capacity [21]. The specifications in [23] were followed when performing the ultrasonic test. Three 40 mm × 40 mm × 160 mm prism specimens were evaluated by/according to [22], to ascertain the flexural strength. An impact test was conducted on a mortar disk of 150 mm in diameter and 63.5 mm in height according to [30]. In the sample center, a 4.536 kg hammer was repeatedly dropped from a height of 0.4572 m onto a 1182 g steel ball. The test was run until every concrete sample failed. The quantity of blows was recorded.

Fig. 1. (a) Glass powder preparation, (b) preparation of aluminum fibers.

TABLE II. MIXES' PROPORTIONS

Mix	C	S.	W/C	SP %	WALF %	POWG
R	350	1050	0.38	1.25	0%	0
F0.25	350	1050	0.38	1.25	0.25%	0
F0.50	350	1050	0.38	1.25	0.5%	0
F0.75	350	1050	0.38	1.25	0.75%	0
F1.00	350	1050	0.38	1.25	1.0%	0
G	350	1050	0.38	1.25	0%	52.5
GF0.25	350	1050	0.38	1.25	0.25%	52.5
GF0.50	350	1050	0.38	1.25	0.5%	52.5
GF0.75	350	1050	0.38	1.25	0.75%	52.5
GF1.00	350	1050	0.38	1.25	1%	52.5

III. RESULTS AND DISCUSSION

A. Workability

The workability has been assessed utilizing the flow table test, which is used for mortar, measuring the diameter of flow. As displayed in Figure 2, adding fiber reduced the diameter of the mix flow, which means less workability compared to the control mix. These outcomes are comparable to those of [24], where it was discovered that mix workability decreased when waste fibers from soft drink tins were used. The flow table test revealed a slight agglomeration in a few locations at 0.75% SF. Replacing cement with 15% POWG reduced the flow from 28.5 mm for the control mix to 26 mm. Incorporating 15% POWG with different percentages of metallic fibers caused an extra decrease in workability.

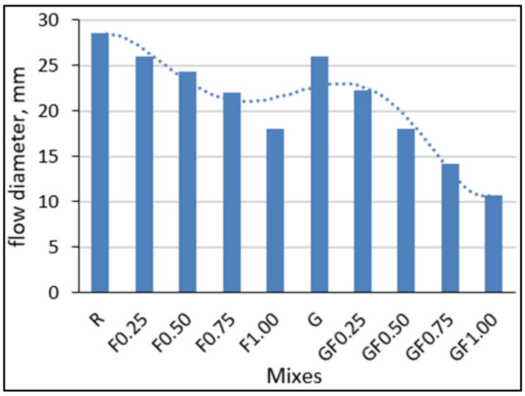

Fig. 2. Flow diameter for all mixes.

B. Compressive Strength

Figure 3 presents the results of the compressive strength tests. The inclusion of Waste Aluminum Fibers (WALF) generally led to a reduction in compressive strength, with the most significant loss observed at 1% WALF. However, when 15% POWG was incorporated into the control mix, the compressive strength increased from 32.5 MPa to 35.6 MPa. The addition of fibers to mixes containing 15% POWG showed different behavior compared to the mixes without POWG. Specifically, the mix with 15% POWG and 0.25% WALF exhibited the highest compressive strength among all the tested combinations. This indicates that glass powder contributes to strength improvement. One likely reason for the reduction in strength with higher WALF content is the weak bond between the aluminum fibers and the mortar matrix, which becomes more pronounced as the fiber content increases. Conversely, the inclusion of POWG appears to improve the interaction between the fibers and the surrounding mortar. This is likely due to the pozzolanic reaction of glass powder, which enhances the bond at the fiber–matrix interface. In Fiber Reinforced Concrete (FRC), this interface—known as the Interfacial Transition Zone (ITZ) separates the fiber surface from the mortar matrix. It is considered a third phase, distinct in properties from both the fiber and the bulk mortar. Depending on variables, such as the fiber surface and concrete composition, the ITZ often exhibits greater porosity, and a different microstructure compared to the bulk material. When fibers are introduced, small binder particles are packed less densely near the fiber surface due to the "wall effect," leading to zones with low-modulus phases, like voids and low-density Calcium Silicate Hydrate (C-S-H). This area also typically contains higher concentrations of Calcium Hydroxide (CH) [25]. Overall, replacing cement with waste powders—such as glass, eggshell, or fly ash—tends to improve the concrete's microstructure by reducing porosity and increasing density.

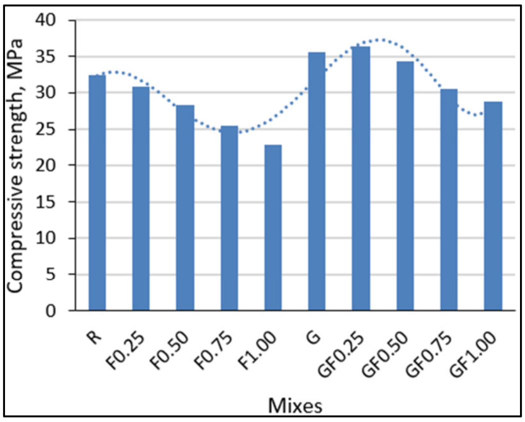

Fig. 3. Compressive strength for all mixes.

The interface extends into the matrix with gradients in several matrix material parameters, such as the water/binder ratio, porosity, degree of hydration, hydrate composition, etc., beginning at the surface where the original fiber and matrix meet [26, 27].

C. Flexural Strength

Figure 4 shows the results of the flexural strength tests. The addition of WALF enhanced the tensile strength of the cementitious matrix, with the highest strength observed at a fiber content of 0.5%. This trend was consistent across all fiber-reinforced specimens. The improved performance is attributed to the bridging effect of the fibers, which helps redistribute stress across adjacent sections rather than allowing it to concentrate at a single crack. This leads to the formation of multiple smaller cracks rather than a single major fracture [28]. Long fibers have been shown to offer excellent crack resistance and reduce the propagation of micro-cracks [3]. Additionally, incorporating 15% POWG into the control mix increased its flexural strength from 3.4 MPa to 3.6 MPa. When fibers were added to mixes containing POWG, the results differed from those of mixes without POWG. Notably, the combination of

15% POWG and 0.5% WALF produced the highest flexural strength among all tested mixes, indicating that glass powder contributes positively to strength development [29].

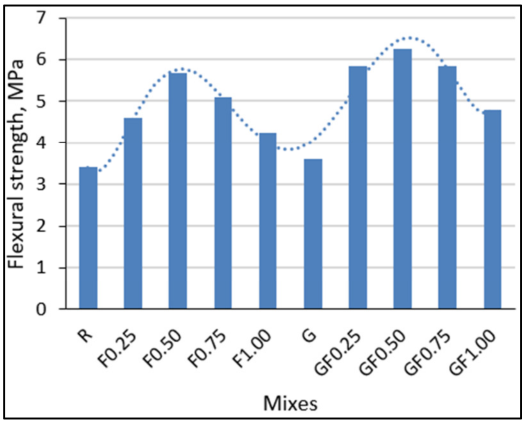

Fig. 4. Flexural strength for all mixes.

The brittle quality of the concrete caused the reference samples to collapse unexpectedly, resulting in poor flexural strength. Adding fibers increases the modulus of rupture because of their capacity to limit the development, enlargement, and spread of cracks. Additionally, the bridging action of the fibers across the fractures will induce a ductile behavior [28].

D. *Ultrasonic Pulse Velocity*

The Ultrasonic Pulse Velocity (UPV) method was utilized as a non-destructive test to evaluate the quality of the mortar. An ultrasonic pulse is timed as it passes through the mortar that is being tested. Compared to when the construction material is of poor quality in terms of homogeneity, unit weight, etc., a higher time is achieved. Figure 5 displays the outcomes of the test. The UPV for the 15% POWG is the highest of all mixes, as shown in Figure 5, and ranged from 4.85 for the control mix to 3.25 for the lowest value for 1% WALF specimens. When aluminum fibers were added, speed dropped as the addition ratio rose in comparison to the reference specimens. This is because the pulse velocity decreases when UPV is partially transmitted via different materials [14]. When 15% POWG was added to the reference mix, the UPV test showed an increase in wave speed compared to the control specimens. This improvement is attributed to the finer glass particles filling voids and gaps within the concrete matrix, resulting in higher density and, consequently, greater pulse velocity. Although the overall density was only slightly affected, the enhanced internal structure due to better particle packing played a key role. UPV testing is especially useful for estimating compressive strength in a non-destructive manner, making it ideal when structural integrity must be preserved during evaluation. The pozzolanic reaction of the glass powder reduces the content of Portlandite CH, which in turn leads to a denser microstructure. As a result, the amount of weak hydration products decreases, and the packing of particles is improved—particularly in the ITZ—thereby reducing porosity and improving the overall quality of concrete.

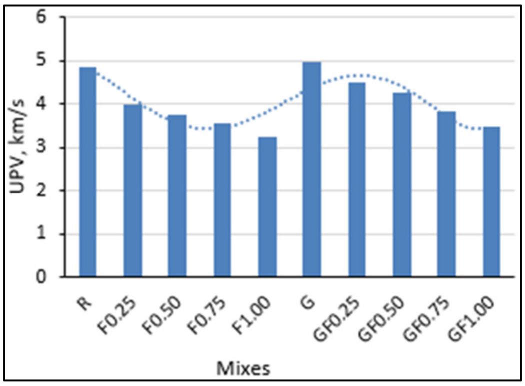

Fig. 5. UPV for all mixes.

E. *Impact Resistance*

The impact resistance of mortar reinforced with WALF was evaluated by counting the number of blows required to cause failure, as portrayed in Figure 6.

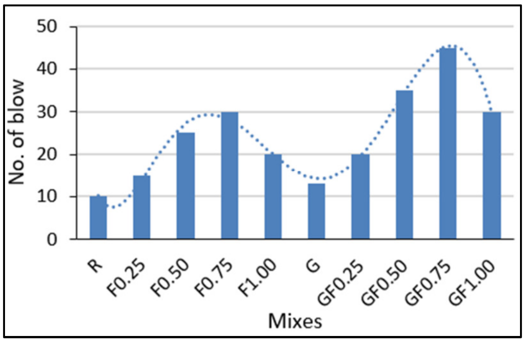

Fig. 6. No. of blows for all mixes.

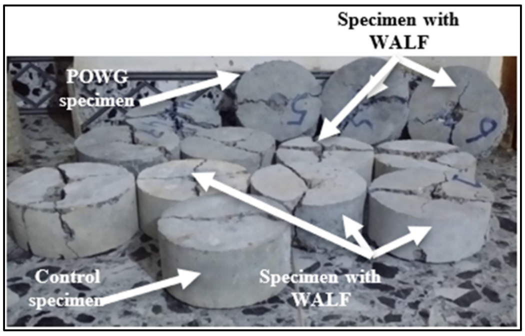

Fig. 7. Shape of failure under impact load for all mixes.

The results indicated that the inclusion of aluminum fibers significantly improved the mortar's resistance to impact. For the group of mixes without glass powder, increasing the fiber content led to a higher number of blows needed to reach failure. All fiber-reinforced specimens exhibited more ductile failure behavior compared to non-fiber mixes. Ductility refers to a material's ability to deform under stress, while stiffness indicates its resistance to deformation. As expected, an increase in ductility resulted in reduced stiffness—an outcome confirmed by the test results. Additionally, Figure 7 demonstrates that the number of visible cracks increased with the addition of fibers in both glass powder and non-glass powder mixes. This crack distribution helps dissipate energy more evenly, reducing the likelihood of sudden, brittle failure.

F. Result Discussion

Adding WALF increased the mortar's tensile strength and impact; the highest strength was recorded at 0.5% WALF. The bridging activity of the fibers leads to loads moving to adjacent areas instead of localizing at a single fracture, so any strength gain after the original crack is the result of multiple subsequent cracks [29]. With the addition of 15% POWG, the control mix's tensile strength rose from 3.4 MPa to 3.6 MPa. Compressive strength decreased when WALF was added, with greater losses observed at 1% WALF. Incorporating 15% POWG into the control mix boosted its strength from 32.5 MPa to 35.6 MPa. The results of adding fibers to mixes that contained 15% POWG differed from the mixes' strength. However, POWG's pozzolanic effect, which strengthens the bond between the fibers and the surrounding mortar, may be the reason why the addition of POWG has produced different reactions in the specimens. Fiber integration to interface with the sound matrix was then made simpler via POWG. Depending on the circumstances (fiber surface, concrete composition), the ITZ could have a higher porosity and a different composition than the bulk material [25]. Glass powder enhances particle packing and decreases the amount of weak hydration products, such as CH, which helps reduce the porosity of the ITZ [25]. However, depending on factors, like the fiber surface and concrete composition, the ITZ may have higher porosity, and a different composition compared to the bulk material [25].

IV. CONCLUSIONS

The present research investigates the behavior of mortar incorporating two types of waste materials: glass powder (used as a partial cement replacement) and aluminum fibers sourced from used soda cans. This approach supports the safe and sustainable use of recycled materials in civil infrastructure and building applications. The findings of this study meet the research objectives and address specific knowledge gaps:

- For all mixes, both with and without POWG, it was observed that the flowability (workability) of fresh mortar decreased linearly as the WALF content increased. The inclusion of POWG further reduced workability.
- In all combinations, with and without POWG, the average wave velocity varied. However, compared to the reference mix, the addition of POWG consistently increased wave velocity, indicating improved internal density.
- The results revealed that mixes containing 15% POWG and WALF had higher compressive strength than the control mix. The highest strength was recorded for the mix with 15% POWG and 0.25% WALF, due to the pozzolanic activity of the glass powder.
- The addition of WALF improved the tensile strength of the cementitious matrix, with the highest strength observed at 0.5% WALF in all fiber-reinforced specimens.
- The tensile strength of the control mix increased from 3.4 MPa to 3.6 MPa when 15% POWG was added. Incorporating fibers into mixes with 15% POWG produced different results compared to those without POWG. The mix with 15% POWG and 0.5% WALF achieved the highest flexural strength among all mixes, confirming the strength-enhancing effect of glass powder.
- The addition of aluminum fibers increased the mortar's resistance to impact. As fiber content increased, so did the number of blows required to cause failure. For all fiber-reinforced mixes—especially those without glass powder—a more ductile failure mode was observed.

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