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Properties of a Low-Carbon Binder-Based Mortar Made with Waste LCD Glass and Waste Rope (Nylon) Fibers

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Abstract: Carbon dioxide emissions are one of the problems that arouses the interest of scientists because of their harmful effects on the environment and climate. The construction sector, particularly the cement industry, is a significant source of CO_2. On the other hand, solid waste constitutes a major problem facing governments due to the difficulty of decomposing it and the fact that it requires large areas for landfill. Among these wastes are LCD waste glass (WG) and used rope waste. Therefore, reusing these wastes, for example, in concrete technology, is a promising solution to reduce their environmental impact. Limited studies have dealt with the simultaneous utilization of glass waste as a substitute for cement and rope waste (nylon) fiber (WRF). Therefore, this study aimed to partially replace cement with WG with the addition of rope waste as fibers. Thirteen mixtures were poured: a reference mixture (without replacement or addition) and three other groups containing WG and WRF in proportions of 5, 15 and 25% by cement weight and 0.25, 0.5 and 0.75% by mortar weight, respectively. Flow rate, compression strength, flexural strength, dry density, water absorption, dynamic modulus of elasticity, ultrasonic pulse velocity and electrical resistivity were tested. The results indicate that the best ratio for replacing cement with WG without fibers was 5% of the weight of cement. However, using WRF increased the amount of glass replacement to 25%, with an improvement in strength and durability characteristics.

Keywords: LCD waste glass; waste rope fiber; mechanical properties; water absorption; electrical resistivity

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1. Introduction

The steady population growth and the accompanying industrial development in various fields have increased demand in the construction sector [1]. One of the fundamental composite substances in this sector is concrete [2]; therefore, the sector's development leads to increased concrete production. This growth is proportionately reflected in the cement industry, which is the main binder in conventional concrete [3]. The cement industry is accompanied by various emissions, including carbon dioxide, which cause global warming and environmental damage [4,5]. Accordingly, scientists have searched for ways to reduce this damage, including reducing the cement content in concrete mixes. This is achieved by replacing it with other materials with fewer emissions, and, among these, are the by-products of other industries and waste [6,7]. On the other hand, solid waste constitutes a great burden on the governments of countries as a result of the difficulty of its decomposition [8]; it may be toxic in addition to its need for large waste dumps for landfills. Accordingly, reusing these wastes in concrete technology has several benefits, including reducing environmental damage and greenhouse gas emissions and converting them into valuable materials [9].

Waste glass is among the wastes used as a substitute for cement. The pozzolanic interaction [10] between waste glass and the calcium hydroxide arising from cement hydration has been cited as one method by which glass waste improves the various properties of concrete. Increasing the production of cement gel (C-S-H) and speeding up the hydration process are also essential factors in this enhancement [11,12]. Additionally, fine glass particles have a filling effect [13], filling the voids between the cement granules or between the cement granules and the fine aggregate, which helps to densify the matrix microstructure and enhance the properties of the concrete.

Several sources of glass waste used for this purpose have been referenced in the literature: those that come from bottles [14], containers [15], neon [16] and liquid crystal displays (LCD) [17]. Among the most common types of waste glass is soda–lime glass because its raw materials are relatively cheap [17]. This glass is chemically different from waste LCD glass; therefore, it may show different behavior in concrete when used as an alternative material. Soda–lime glass is composed of silica (SiO_2), calcium oxide (CaO), sodium oxide (Na_2O), NaO and CaO, while LCD glass has almost no alkali content [17,18]. In addition, because the LCD panel production line requires high-temperature processing of 300 °C or higher, LCD glass has excellent chemical durability. Thus, alkali-free alumino borosilicate glass can be used in LCD glass [17,19].

The utilization of glass in products such as LCD screens and modern smartphones has increased exponentially [20]. Informal recycling and disassembly methods of waste LCD glass panels are being implemented, thus spoiling the environment and soil [20]. The composition of LCD waste glass sometimes fluctuates due to the use of different products [21]. The reuse of these wastes as cement replacement material is a worthwhile solution. Waste LCD glass has been used previously by several studies. For instance, Wang (2011) [22] investigated the fresh and hardened properties of mortar made with 0% to 50% (in 10% steps) TFT–LCD (thin-film transistor–liquid crystal display) glass waste as a cement-replacing material. Results indicated that the higher the percentage of glass, the lower the compressive, flexural and tensile strengths. Moreover, it was found that a maximum of 10% of TFT–LCD glass could be used to give improved durability characteristics and almost comparable flexural and compressive strengths to those of the control mixture. Lee and Lee (2016) [23] investigated the potential use of TFT–LCD glass as a concrete binder. The results indicated that up to 10% of glass resulted in improved strength and durability properties. However, at 20% replacement, these properties were negatively affected due to the hardened cement system's porous structure. Raju et al. (2021) [20] investigated the substitution of cement with glass waste within the 5 to 20% range. The best percentage for mechanical properties was found to be 5%, while the 20% replacement rate was the best percentage for durability properties. Yang et al. (2021) [24] studied the influence of LCD glass as an alternative to cement in proportions of 10% and 20% on concrete properties such as strength, hydration and durability. Results revealed that the glass waste improved the concrete properties by at least 5% at later ages (28 days). Moreover, it was concluded that up to 20% of the cement could be substituted with fine LCD glass.

Otherwise, using fibers to reinforce concrete improves its mechanical, durability and ductility properties. Several types of industrial and waste fibers have been used in previous studies [25]. Among these fibers are waste plastic fibers [26]. These fibers are considered a promising solution for developing the properties of concrete (depending on their type and proportion) on the one hand and for improving sustainability on the other hand, as they are solid wastes that affect the environment negatively. Many researchers have used waste plastic fibers in concrete. For instance, Al-Hadithi and Hilal (2016) [27] investigated the influence of waste plastic fibers from cutting beverage bottles (PET) on SCC's fresh and hardened properties. It was found that the PET decreased the fresh characteristics of SCC while the flexural and compressive strengths were improved. Abdulridha et al. (2021) [28] studied the mechanical and structural behavior of concrete-incorporated waste rope fibers (WRF) in proportions of 0%, 0.25%, 0.5% and 1% by weight of concrete. It was found that WRF enhanced concrete's compressive strength and flexural strength by 22% and 4.3%, respectively. On the other hand, Jain et al. (2019) [29] explored the effect of adding shredded waste plastic bags (SWPB) in the percentages of 0, 0.5, 1, 2, 3 and 5% by concrete weight on concrete properties. The results indicated that both the fresh and hardened properties were affected negatively by adding SWPB.

According to the above literature, very limited studies have examined the effect of plastic fiber waste, specifically waste rope fiber, on the properties of mortar containing LCD waste glass as an alternative to cement. Thus, the current study aims to investigate the mechanical and durability properties of mortar made from various proportions of glass waste (5, 15 and 25%) with the addition of different proportions of WRF. It is believed that the findings of this study are promising as a result of improving the different properties of mortar and its contribution to the development of sustainability as a result of raising the percentage of replacing cement with WG (in the presence of fibers) to 25% and thus reducing the environmental damage of these residues and reducing harmful emissions associated with the cement industry as a result of minimizing its quantity in the mix.

2. Experimental Program

2.1. Materials

2.1.1. Cement

Locally produced CEM II/A-L 42.5 R-type limestone cement was used to prepare all mortar mixtures. The cement's specific gravity, fineness and particle size were 3.05, 399 m^2/kg and 17.99 µm, respectively. Table 1 presents the chemical properties of the cement conforming to Iraqi Standard (IQS) No. 5 [30]. Figure 1 illustrates the particle size distribution of the cement.

Table 1. The chemical composition of the cement and waste glass.

	Content, %	
Oxide, %	**Cement**	**LCD Waste Glass**
SiO_2	16.91	59.75
CaO	60.51	1.401
Fe_2O_3	4.360	---
Al_2O_3	3.194	2.093
SO_3	3.146	0.057
MgO	2.479	0.611
Na_2O	1.429	6.866
K_2O	0.495	7.025
SrO	0.0913	6.647
Ba	0.033	6.471
L.O.I.	3.1	---

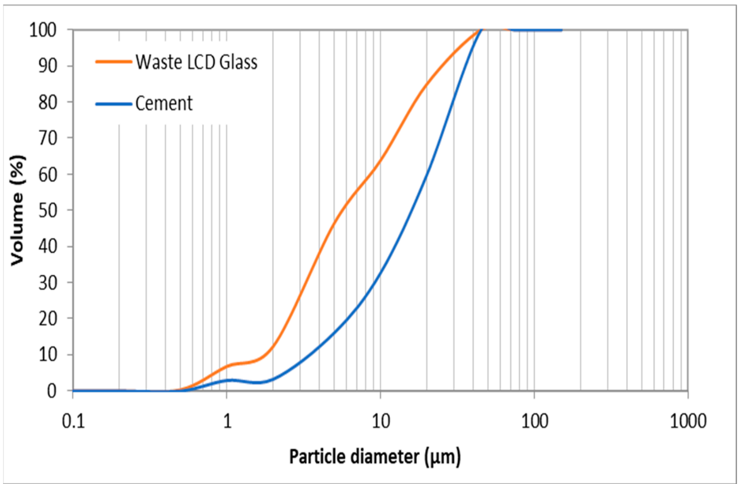

Figure 1. The particle size distribution of the cement and waste LCD glass.

2.1.2. Waste Glass

Glass waste powder (Figure 2) was prepared by manually crushing old LCD screens and then it was ground in a Los Angeles machine. The TV screens were brought from a local repair shop. These screens generally belonged to old, broken or damaged televisions. There are currently no local technologies that reuse the waste of these screens, so they are disposed of in landfills. To utilize them in this research, the screens were cleaned, broken into smaller fragments and washed to eliminate any dirt or dust. Subsequently, they were left to dry for a specific duration before being ground. Thereafter, they were passed through sieve No. 200 (75 microns) and used as a substitute for cement. Cement was substituted (by weight) with waste glass powder in proportions of 5, 15 and 25%. The fineness of the glass was 450 m^2/kg, and the D50 was 5.498 µm. The granular distribution of the waste glass and the chemical analysis are shown in Figure 1 and Table 1, respectively.

Figure 2. The waste glass used.

2.1.3. Fine aggregate

Natural sand (locally available) with a grain size of 0.15–4.75 mm was utilized as a fine aggregate in the mortar mixtures. The grading results of the fine aggregate are shown in Table 2, which indicates its conformity with Iraqi Standard No. 45 [31].

Table 2. The sieve analysis results of the sand.

Sieve No. (mm)	Passing (%)	Iraqi Specification, IQS No. 45
4 (4.75)	91	90–100
8 (2.36)	83	75–100
16 (1.18)	74.8	55–90
30 (0.6)	57.2	35–59
50 (0.3)	24.2	8–30
100 (0.15)	7.2	0–10

2.1.4. Waste Rope Fibers

Nylon is a synthetic, silky thermoplastic material that can be melted and processed into various shapes, films or fibers [32]. Nylon (plastic) fibers are used in the production of multiple products such as carpets, ropes, clothes, tires and other durable materials [32]. According to the literature [33], the performance of concrete reinforced with short plastic fibers increases significantly. In contrast, the shortcomings of concrete, such as its poor tensile strength, low ductility and low energy absorption capacity, are eliminated. As a result, incorporating plastic waste fibers into concrete is a viable strategy for enhancing concrete properties and mitigating its negative effects on the environment. The waste rope fibers (WRF) that were used in this study were prepared by cutting nylon ropes with a thickness of 0.19 mm into pieces of 15 mm in length (see Figure 3) and then used to reinforce the mortar containing the glass waste. The aspect ratio, tensile strength and modulus of elasticity of the fibers were 79, 600 MPa and 2.66 GPa, respectively.

Figure 3. The waste rope fibers used.

2.1.5. Water

Tap water was employed for mixing the mortar ingredients in all mixes.

2.2. Mix Proportions

Three groups of mixtures containing glass waste and fiber waste, in addition to the reference mixture (free of glass and fiber), were implemented. In each group, fiber was added in three percentages (0.25, 0.5 and 0.75% by weight) while the first, second and third groups involved replacing cement by weight with 5, 15 and 25% of glass waste. The water/binder ratio and amount of sand were fixed for all mixtures. Details of the poured mixes are illustrated in Table 3.

Table 3. Mix details of the mortar mixture as a weight ratio of the total binder materials (cement + waste glass).

Mix Designation	Cement	Sand	Waste Glass	Waste Rope Fibers *	Waste Rope Fibers (by Vol.) **	Water/Binder
Control	1	2.75	0.0	0	0	0.485
WG5	0.95	2.75	0.05	0	0	0.485
WG15	0.85	2.75	0.15	0	0	0.485
WG25	0.75	2.75	0.25	0	0	0.485
WG5F0.25	0.95	2.75	0.05	0.0025	0.001	0.485
WG15F0.25	0.85	2.75	0.15	0.0025	0.001	0.485
WG25F0.25	0.75	2.75	0.25	0.0025	0.001	0.485
WG5F0.5	0.95	2.75	0.05	0.005	0.002	0.485
WG15F0.5	0.85	2.75	0.15	0.005	0.002	0.485
WG25F0.5	0.75	2.75	0.25	0.005	0.002	0.485
WG5F0.75	0.95	2.75	0.05	0.0075	0.003	0.485
WG15F0.75	0.85	2.75	0.15	0.0075	0.003	0.485
WG25F0.75	0.75	2.75	0.25	0.0075	0.003	0.485

* The fiber content was calculated by the weight of the mortar. ** The fiber content was calculated by the volume of the mortar.

2.3. Mixing, Casting and Curing of Mortar Mixtures

The mortar components were mixed using a two-speed mechanical mixer, slow and high, according to the following steps:

- All dry ingredients (without fibers) were mixed for 1 min at a slow speed (140 rpm);
- Then, water was added while the mixer was running, and the mixing continued for 1 min at the slow speed;

- After that, the mixer was stopped for 30 s, the speed was changed to the high one (285 rpm) and the wet materials were mixed for 1 min;
- After that, the fibers (if any) were added within 30 s while the mixer was in operation at high speed, and the mixing continued for 1.5 min.

After mixing, the fresh mortar was cast into standard molds (50 × 50 × 50 mm^3 and 40 × 40 × 160 mm^3). After about 23–24 h, the molds were lifted, and the specimens were immersed in water until the examination day.

2.4. Tests

2.4.1. Flow Rate

The flow rate of the fresh mortar was calculated directly after the end of the mixing process according to ASTM C1437 [34].

2.4.2. Compressive Strength

Compressive strength was measured using 50 mm cubes by dividing the failure load by the cube sectional area following ASTM C109 [35] (see Figure 4a). The examination was carried out at the ages of 28 and 56 days. An average of three readings was adopted for each age.

Figure 4. Some images of the experimental tests: (**a**) compressive strength, (**b**) flexural strength, (**c**) UPV and (**d**) electrical resistivity.

2.4.3. Flexural Strength

Flexural strength was calculated using 40 × 40 × 160 mm^3 prisms according to BS EN 196-1 [36] (Figure 4b). The examination was performed at 28 days. An average of three readings was adopted.

2.4.4. Bulk Density and Water Absorption

The dry bulk density and water absorption were determined following the procedure described in ASTM C642 [37] using prism halves tested under the flexural machine. An average of three specimens was used. The tests were performed at 28 days.

2.4.5. Ultrasonic Pulse Velocity (UPV) and Dynamic Elastic Modulus (Ed)

The ultrasonic pulse velocity (UPV) and dynamic elastic modulus were examined at 28 days of age using a 50 mm cube according to the method described in ASTM C597 [38] (see Figure 4c). An average of 3 readings (3 cubes, one reading from each cube) was taken. Equation (1) was used to calculate the Ed depending on the velocity and density [38].

$$v = \sqrt{\frac{\mathrm{Ed}(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (1)$$

where Ed is the dynamic elastic modulus, μ is the dynamic Poisson's ratio (which was taken as 0.2 [39]), v is the velocity and ρ is the density.

2.4.6. Electrical Resistivity

The electrical resistivity of the mortar specimens was investigated using the two-metal plate method [40]. The specimens were examined when they were in a full saturation (with moisture) state as they were examined after they had been taken out of the curing water and wiped with a towel. A cube of 50 mm was placed between the two plates, and a damp sponge was placed between the plate and the cube to ensure good connectivity. Two pieces of wood were placed above and below the cube, and a weight of 4 kg was placed on the wooden pieces (see Figure 4d). An LCR meter was used to measure the impedance, and a frequency of 1000 Hz was applied [41]. Then, the electrical resistivity of the specimen was calculated using Equation (2). The examination was executed at 28 days, and an average of 3 readings was adopted for each result.

$$ER = \frac{A}{L} R \quad (2)$$

where

ER: the electrical resistivity (Ω·cm);
R: the impedance (or the electrical resistance in AC);
A: the specimen's cross-sectional area in cm^2;
L: the height of the specimen in cm.

3. Results and Discussion

3.1. Flow Rate

Figure 5 shows the flow test results for the mortar mixtures containing glass and fiber waste. The results show that the mixtures WG (without fibers) had a flow rate that exceeded that of the reference mixture. The highest flow rate was recorded for the WG5 mixture, with an improvement of 14%. After this ratio, the flow rate tended to decrease with the increase in the glass content. However, even with a 25% replacement, the flow rate still exceeded that of the control specimen. The enhancement of the flowability of waste-glass-based mortar can be attributed to the smooth surface of the glass [42] and its cleaner nature [10]. The tendency of the flow to decrease at high glass content (beyond 5%) may be due to the large surface area of the glass and the small size of its grain compared to cement; therefore, it needs more water to be wetted.

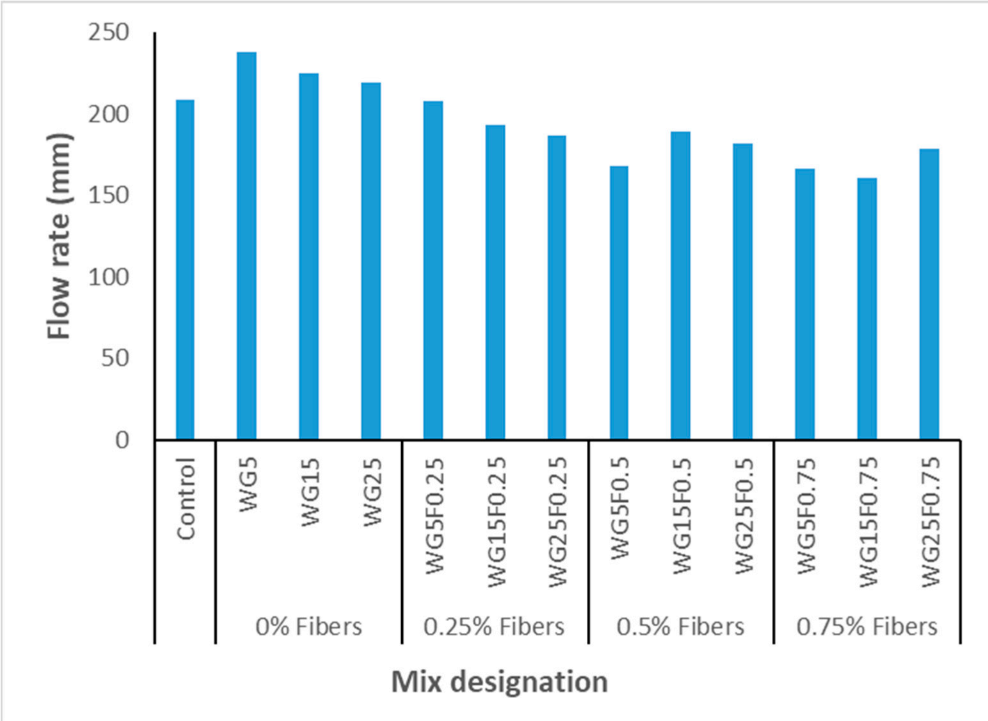

Figure 5. Results of the flow rate of fresh mortars.

Moreover, the results show that adding fibers led to a drop in the flow rate of the fresh mortar for all mixtures containing fibers except for the WG5F0.25 mixture, which had a flow similar to that of the reference sample. The flow rate of the mixtures containing fibers ranged between 7.4 and 10.6%, 9.4 and 19.6% and 14.2 and 22.9% at fiber percentages of 0.25, 0.5 and 0.75%, respectively. This decline in workability can be attributed to the fact that the WRF interrupts the viscous characteristics of fresh mortar and limits the formation of a stable mixture, thus reducing flowability [43].

3.2. Compressive Strength

The compressive strength results of mortar mixtures are shown in Figure 6. The results show that, for mixtures containing glass waste, using 5% glass as a substitute for cement gave compressive strength that exceeded the reference mixture by 32.8 and 31.8% at 28 and 56 days, respectively. These results are in agreement with the literature [20]. At replacement rates of 15 and 25%, the compressive strength decreased by 19.4% and 26.1% at the age of 28 days and 9.5% and 23.9% at the age of 56 days, respectively. These results are also consistent with the findings of Zeybek et al. [44], which stated that replacing cement with glass waste at rates of 10 to 50% (in 10% steps) causes a decrease in compressive strength within the range of 3 to 37%. The enhancement in compressive strength at 5% can be attributed to the effect of filling the voids of the glass granules due to their smallness compared to the cement granules, in addition to the pozzolanic reaction of the glass waste with calcium hydroxide resulting from the hydration of the cement [45]. The negative effect of compressive strength at the 15 and 25% ratios was due to increasing the effective water–cement ratio and reducing the cement content (the dilution effect) [46]. However, when observing the values of the compressive strength for these two percentages, it was noted that the decrease in the strength decreased with time as the reduction declined from 19.4% to 9.5% for glass content 15% and from 26.1% to 23.9% for a glass content of 25%. This indicates the role of the pozzolanic reaction of glass in improving the strength, which is more prominent at later ages (after 28 days).

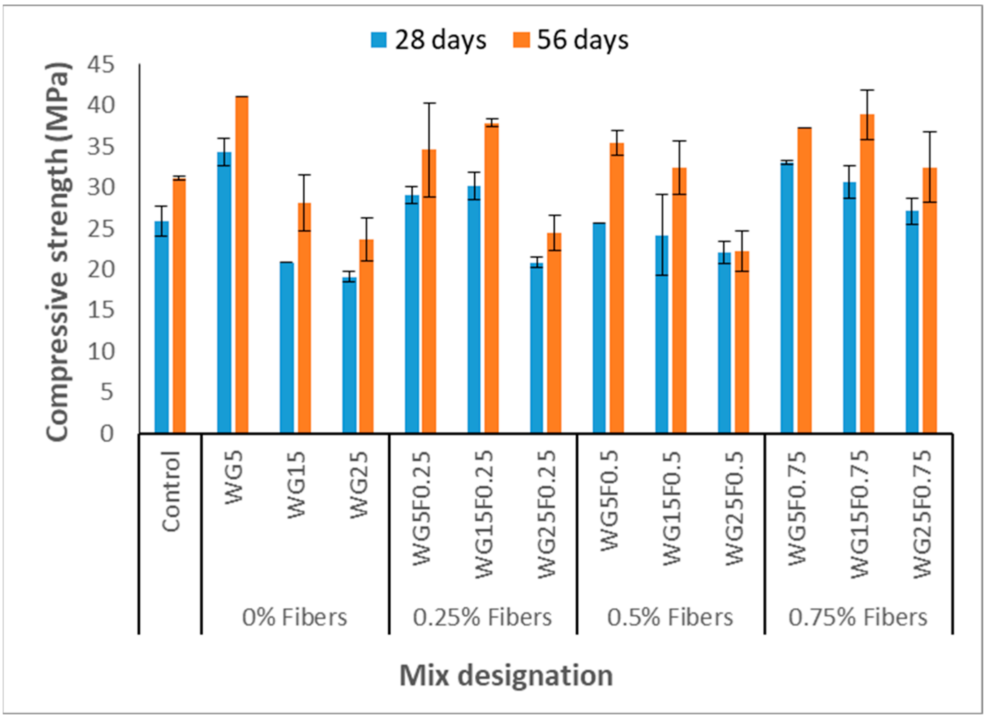

Figure 6. The compressive strength results of mortar mixtures at 28 and 56 days.

Moreover, in general, the results show that the presence of fiber residues led to a clear improvement in the compressive strength of most of the mixtures compared to the control mixture. It was found that at 0.25% fiber, the compressive strength increased in relation to the plain mortar by 12.4 and 16.8% at 28 days and 11 and 21.5% at the age of 56 days for the mixtures WG5F0.25 and WG15F0.25, respectively. Similar findings were also recorded in a previous work [47]. In contrast, 25% glass reduced the strength by 19.4% and 21.5% at the ages of 28 and 56 days, respectively. On the other hand, adding fibers at 0.5% decreased the compressive strength by 0.8, 6.5 and 14.7% at the age of 28 days at a glass content of 5%, 15% and 25%, respectively. However, at 56 days, the glass content of 5% and 15% gave an improvement of 13.8 and 3.9%, while, for the WG25F0.5 mixture, the reduction in compressive strength continued. Furthermore, it can be seen from the figure that adding 0.75% waste fibers led to improved compressive strength of the waste-glass-based mortar for all replacement rates (5, 15 and 25%) and at all ages (28 and 56 days). The improvement rates were 27.9, 18.6 and 4.9% at 28 days and 19.6, 24.8 and 4.2% at 56 days. The reason for the improved strength in the presence of fibers is the contribution of the fibers increasing the final load of the mortar. This increase can be explained, according to the literature [27,48], by the fact that, when microcracks develop in the matrix, the fibers located near these microcracks try to stop these cracks and prevent further spread (bridging effect). Hence, the cracks that appear within the matrix must take a zigzag path, creating a request for more energy to propagate in the future.

3.3. Flexural Strength

The results of the flexural strength examination of the hardened mortar for all mixtures are displayed in Figure 7. The results show that 5% of glass waste gave a higher resistance of 39.5% for the glass-free and fiber-free mixtures than for the reference mixture. This may be due to the mechanical approach of the glass granules that compacts the mortar structure due to their small size and high surface texture in addition to the bonding strength that arises from their pozzolanic reaction [49]. However, by increasing the replacement percentage to 15% and 25%, the flexural strength decreased slightly (7% and 3.9%, respectively) compared to that of the control sample. The dilution effect may explain this reduction in flexural strength. A similar path to the results was recorded by Raju and Rakesh [20], who found that a content of 5% glass provided the greatest value of flexural strength. When the percentage of LCD glass in the mixture was raised, the flexural strength tended to drop, and the lowest values were obtained at 15% and 20% LCD glass content (lower than the glass-free mixture by 2.85% and 5.71%, respectively).

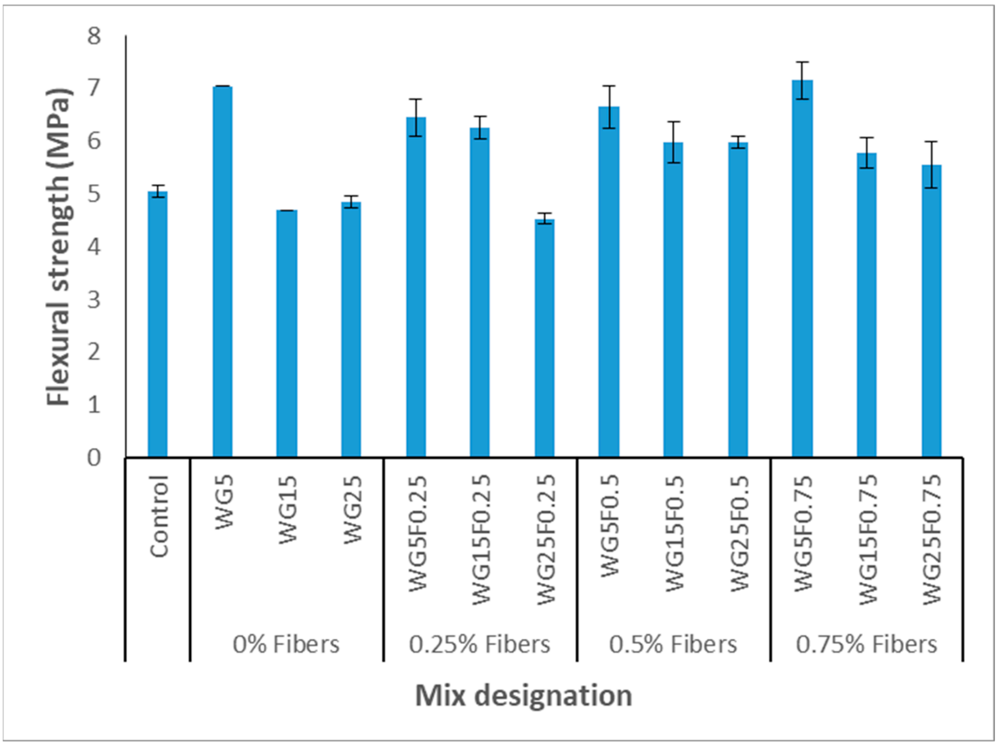

Figure 7. The flexural strength results of mortar mixtures.

Moreover, the results show that the mixtures containing fibers had a clear improvement in the flexural resistance of the mortar containing glass waste for all fiber ratios, except for the WG25F0.25 mixture, which recorded a decrease of 10.1% compared to the reference mixture. The improvements were within the ranges 24 to 27.9%, 18.6 to 31.8% and 10.1 to 41.9% for the fiber ratios 0.25, 0.5 and 0.75%, respectively. These findings align with the information in the literature [47]. This improvement can be attributed to the fact that fibers resist the expansion of cracks resulting from the application of loads and create bridges between the two sides of the crack and delay the failure of the sample, which drives an excess in the flexural strength of the mortar [50].

3.4. Dry Density

Figure 8 shows the dry density results at 28 days for the mortar mixtures containing glass and fiber waste. The figure shows that the change in the dry density values for most of the mixtures did not exceed 1% compared to the reference mixture. The mixtures containing glass as a replacement for cement recorded densities of 2063.2, 2028.6 and 2026.5 kg/m^3 (or 0.9, −0.8 and −0.9%) for 5, 15 and 25% replacement rates compared to 2044.5 kg/m^3 for the control sample. Moreover, the addition of nylon fibers did not cause a substantial change in this behavior. The lowest density was recorded in the WG25F0.25 mixture and was 2024.1 kg/m^3 (or 1% less than the reference mixture density), while the highest density was given by the WG5F0.75 mixture and was 2066.7 kg/m^3 (or 1.1% higher than control sample density). Similar results were recorded previously [28].

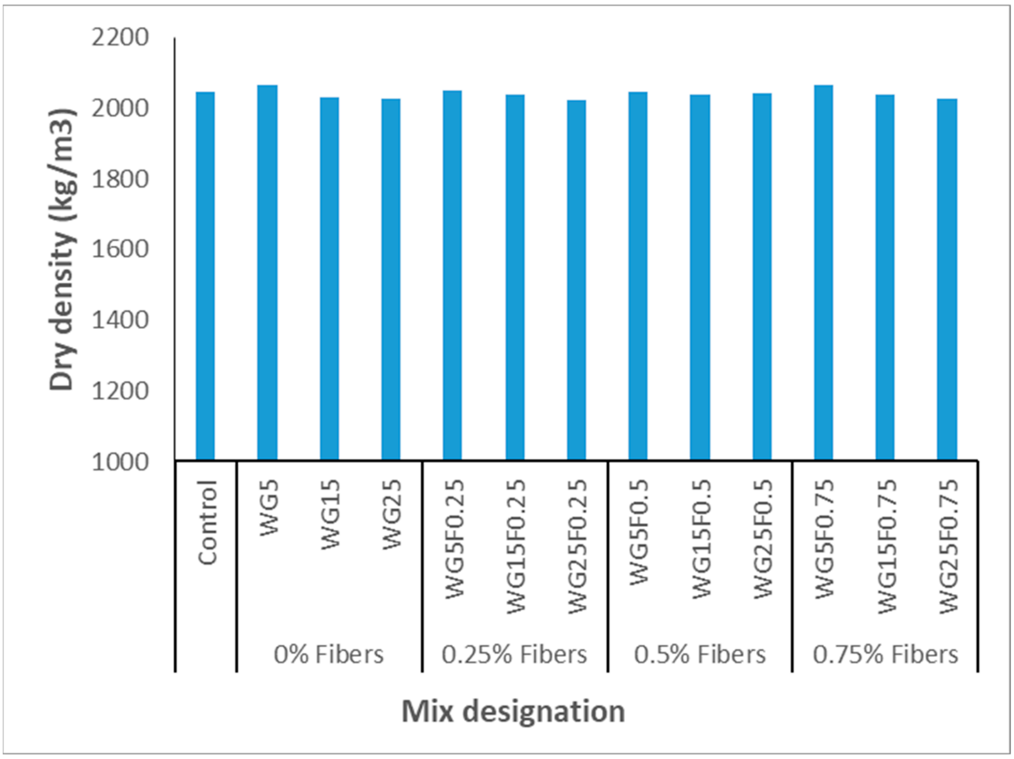

Figure 8. The dry density results of mortar mixtures.

Employing WG as a replacement for cement is believed to cause a decrease in the composite density due to the smaller specific gravity of glass waste compared to cement. However, in this study, the density was equivalent to the glass-free mixture or slightly more in the 5% replacement. This was explained by Nassar and Soroushian, who [51] reported a growth in the density of concrete containing waste glass instead of cement. They attributed this behavior to the densifying of the microstructure as a result of the filling effect, as well as to the pozzolanic activity of the glass, which converts calcium hydroxide to CSH; since the CH has less specific gravity than the CSH [51,52], it contributes to the increase in the density.

3.5. Water Absorption

Figure 9 presents the water absorption results for the mortar mixtures. In general, the results show that the water absorption values of the reference mixture and the mixtures containing glass waste and fiber waste were less than 10%. According to the literature [50], this indicates that the mortar produced for all mixtures was of good quality and durability. The adsorption values of the mixtures containing glass waste were 8.29, 8.45 and 8.11% for WG5, WG15 and WG25, respectively, compared to 8.06% for the reference mixture. For mixtures containing fibers, it was revealed that the highest absorption value was given by the WG25F0.25 and WG25F0.75 mixtures, which was 8.48% (or higher than that of the control mixture by 5.2%). In contrast, the lowest absorption rate was recorded by the WG5F0.75 mixture (the improvement rate was 8.5%). This reduction can be attributed to the minimized pore spaces in the mortar due to the role of fibers in holding the mortar matrix together [53]. In addition, the improvement in the microstructure and reduction in the permeability of the mortar resulted from filling the small waste glass granules of the voids inside the mixture and improving the packing of the particles [54].

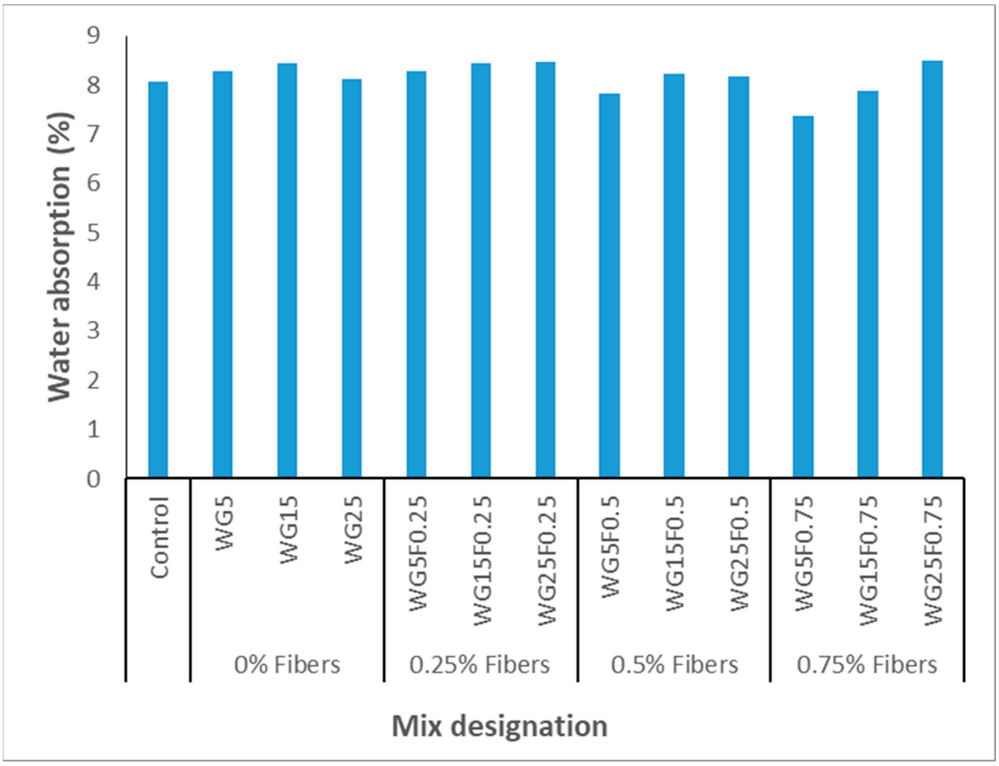

Figure 9. The water absorption results of mortar mixtures.

3.6. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) test is commonly used to evaluate the quality of concrete and involves measuring the electronic wave passing through the material (concrete) [55]. Figure 10 shows the UPV results of the mortar mixtures at 28 days. In general, the results reveal that the presence of glass waste alone in the mixture (without fibers), at a content of 5%, gave a speed value similar to the reference mixture, while it led to a slight reduction with the higher content: 2.2 and 3.6% at replacement rates of 15 and 25%, respectively. Otherwise, adding fiber contributed to reducing this reduction and even gave higher values than the control sample for some percentages. For example, the highest velocity values for each fiber addition group were recorded in the mixtures WG15F0.25 (1.1% improvement), WG5F0.5 (2.4% improvement) and WG5F0.75 (1.6% improvement). In comparison, the lowest speed value among all the mixtures was 2.1%, which was given by the WG25F0.75 mixture. According to Saint-Pierre et al. [56], UPV is a function of the density, shear modulus and bulk modulus of the substance. Thus, concrete cracking and porosity affect UPV as they directly influence the above properties.

Furthermore, mixtures can have various densities, which leads to differences in UPV that correlate with the level of deterioration. In other words, the presence of waste glass that is less dense than cement as an alternative may lead to a decrease in UPV due to the difference in density. Moreover, the cement-based compound's quality (and thus durability) can be classified according to the UPV values as excellent, good, questionable, poor and very poor [57,58]. The range of speed values recorded for mortar mixtures in this study was 4076–3896 m/s. According to the above criteria, the classification of the mortar was of good quality (durability).

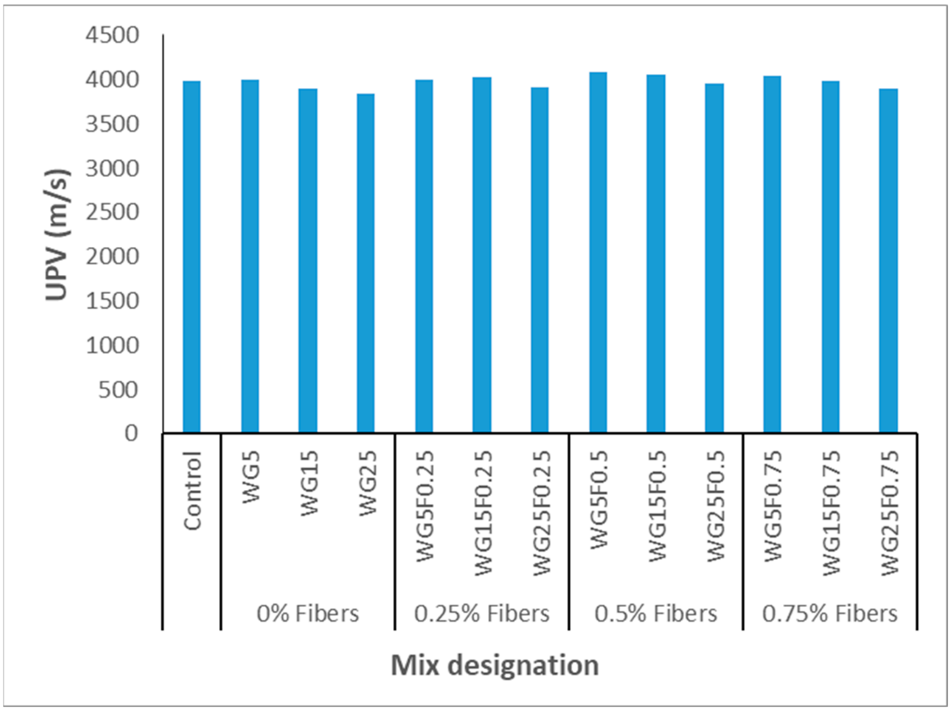

Figure 10. The UPV results of the mortar mixtures.

3.7. Dynamic Modulus of Elasticity

The results of the dynamic elastic modulus (Ed) testing are shown in Figure 11. The results show that the dynamic modulus of elasticity had a trend almost similar to the UPV results. For samples containing waste glass (without fibers), a slight improvement in Ed at 5% replacement was observed, indicating the lack of voids in the mortar matrix. In contrast, Ed decreased by 5.1% and 7.9% when the replacement rate increased to 15% and 25%. This may be due to the lower density of waste glass compared to cement in addition to the presence of voids in these mixtures. Moreover, the addition of fiber improved the Ed values. The highest improvement in modulus of elasticity (5% higher than that of the reference specimen) was found in the WG5F0.5 mixture. Moreover, the mixtures containing 15% glass gave a modulus of elasticity that was higher by 1.9 and 3.5 when adding 0.25% and 0.5% fibers (WG15F0.25 and WG15F0.5 mixtures) than that of the control specimen and an equivalent value to the reference mixture at 0.75% fiber content (WG15F0.75 mix). Furthermore, at 25% waste glass, the reduction in Ed declined from its initial value (−7.9% without fibers) to −4.1%, −1.8% and −5% after adding 0.25, 0.5 and 0.75% of waste fibers, respectively. According to T. Simões et al. [59], the dynamic modulus appears to be related to porosity. The higher the dynamic modulus, the lower the porosity. Thus, the current study's finding indicates that the fibers in a particular proportion work together with waste glass to reduce the porosity within mixtures, which leads to an improvement in the dynamic elastic modulus.

3.8. Electrical Resistivity

Electrical resistivity is one of the most significant characteristics of concrete durability as it is an important parameter influencing rebar corrosion in reinforced concrete [60]. In general, the lower the electrical resistivity, the greater the possibility of corrosion of rebar in concrete [61]. The electrical resistivity values of the mixtures containing glass waste and waste fibers and the control mixture are presented in Figure 12. The results indicate that the electrical resistivity of all mixtures containing glass waste with or without fibers showed an electrical resistance that exceeded that of plain mortar. The mixtures containing glass waste showed that the higher the glass content in the mixture, the greater the electrical resistivity. The electrical resistivity values were higher by 4.5, 6.1 and 15.8% for the WG5, WG15 and WG25 mixtures, respectively, compared to the glassless mixture. This indicates that replacing the cement with glass waste made the mortar more dense and durable. Similar findings were also recorded in a previous work [62]. Moreover, the inclusion of WRF significantly improved the electrical resistivity of the glass waste mortar. The improvement values ranged approximately between 43.8% (WG5F0.25) and 66.7% (WG25F0.25), 82.4% (WG5F0.5) and 126.1% (WG15F0.5) and 110.2% (WG5F0.75) and 150% (WG15F0.75 and WG25F0.75) for the fiber contents of 0.25%, 0.5% and 0.75%, respectively. This may be because plastic fibers have a high electrical resistance [63].

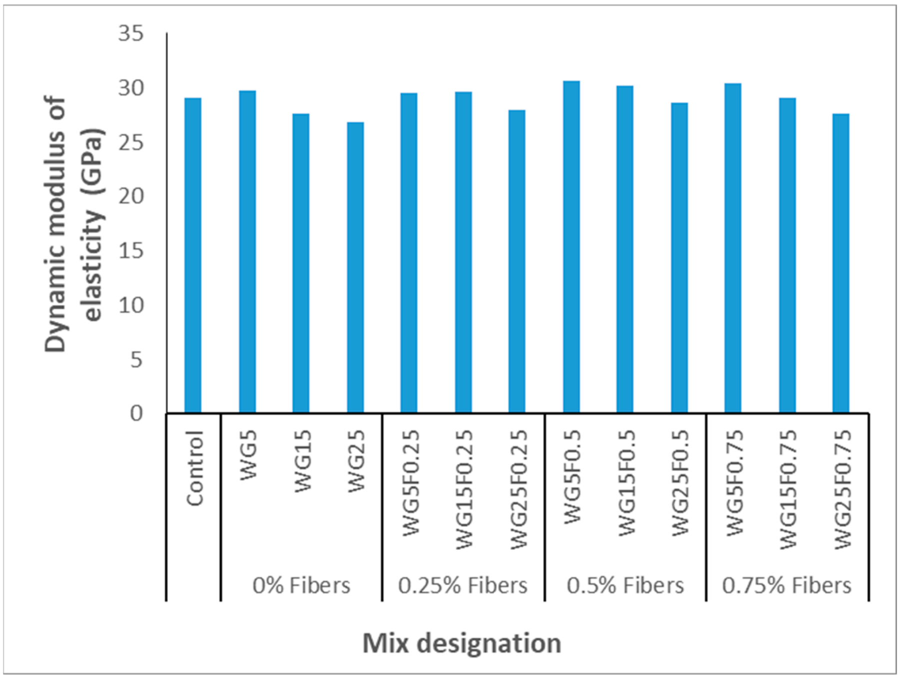

Figure 11. The dynamic modulus of elasticity for mortar mixtures.

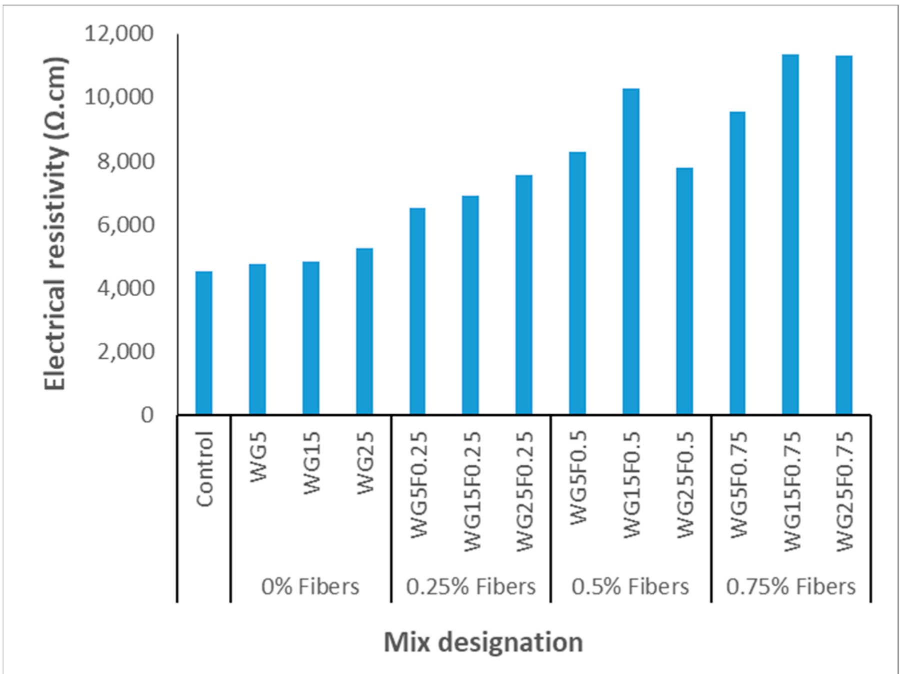

Figure 12. The electrical resistivity results of mortar mixtures.

4. Conclusions

This study investigated the impact of adding WRF fibers on the characteristics of mortar containing waste LCD glass. Cement was replaced with three percentages of waste glass (5, 15 and 25%), and fibers were added in percentages (0, 0.25, 0.5 and 0.75%) of the mortar weight. From the obtained results, the following was concluded:

1. Glass waste improves the flowability of fresh mortar. The highest flowability improvement (14%) was recorded at a 5% replacement rate. When adding fibers, the flow rate decreased for all mixtures except for WG5F0.25, where a flow comparable to that of the control sample was recorded;
2. The use of 5% glass waste improved the compressive strength of the mortar by about 32%. However, the higher replacement ratios (15 and 25%) recorded a compressive strength of less than that of the reference mixture, although the decrease decreased at 56 compared to 28 days. However, the addition of fibers contributed to the improvement of the compressive strength of most mixtures at the considered ages. The highest improvement (24.8%) at 56 days was recorded for the mixture WG15F0.75;
3. Using WG as a replacement for cement improved the flexural strength at 5% compensation, while the strength decreased slightly after that. The addition of fibers boosted flexural strength, especially at the high replacement rates (15% and 25%). The greatest improvement in flexural strength was recorded with WG5F0.75, 41.9% more than the plain mortar;
4. Glass and fiber wastes did not affect the dry density of the mortar, as the change from the control mixture did not exceed 1.1%, whereas, the maximum water absorption of the waste-glass-based mortar was 4.9% for WG15 (without fibers). In the presence of plastic fibers, the WG25F0.25 and WG25F0.75 mixes recorded the highest absorption (higher than that of the control mixture by 5.2%). On the contrary, the lowest absorption rate was recorded by the WG5F0.75 (the improvement rate was 8.5%);
5. The UPV and elastic modulus recorded comparable values at 5% WG and a slight decrease beyond that. After adding fiber, the improvement continued at 5% WG, and the reduction diminished at the higher proportions;
6. Replacing cement with glass waste improved electrical resistivity by up to 15.8% without fibers (WG25) and up to 150% with fibers (WG25F0.75);
7. In summary, according to all the tests carried out, it was demonstrated that the utilization of rope waste fiber in a proportion of 0.75% together with WG gives the possibility of replacing the cement with 25% waste glass with a critical enhancement in the mechanical and durability properties. This helps improve sustainability in several ways, including reducing emissions by an amount equal to the quantity of cement saved, repurposing solid waste and eliminating the environmental damage caused by the waste in the first place. Furthermore, using waste (rope fibers) to enhance the qualities of a structural material made from other waste (LCD glass waste) is a key distinction between our study and what has been stated in the literature. This approach is hoped to pave the way for developing ecologically friendly construction materials with desirable qualities incorporating multiple forms of solid waste.

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