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Experimental Evaluation of Recycled Glass Fiber and Pozzolanic Additives on the Mechanical Performance of Concrete

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Abstract.

The research focuses on using recycled materials to improve concrete behavior in less developed countries, addressing inefficiency, access, and costs. Recent research confirms that recycled materials improve concrete behavior, but significant gaps remain in effectively utilizing non-local materials and additives. This study employed controlled laboratory experiments using standardized protocols to evaluate the effects of recycled fibers, glass waste, and additives on concrete; samples included microsilica, metakaolin, nanosilica, and glass fiber. First, a reference sample (without fibers and additives) was prepared and subjected to various experiments. Following testing, the compressive strength, modulus of rupture, and post-cracking load-bearing capacity of the specimens were evaluated. Approximate equations were also presented to estimate the results of compressive strength, modulus of rupture, and load-bearing capacity after cracking, which were in good agreement with experimental results. The addition of 10% and 15% microsilica increased compressive strength by 12% after 7 and 28 days, respectively. Conversely, incorporating 2.5% glass fiber reduced compressive strength by 16.75% and 11.3% in 7-day and 28-day samples, compared to the reference sample. The modulus of rupture was greatly affected by the addition of glass fiber and increased. Furthermore, the load-bearing capacity of the samples increased after cracking with the addition of microsilica.

Keywords:

concrete, recycled fibers, glass waste, compressive strength, flexural strength

1. Introduction

Over the last two decades, various practical and research efforts have been made to reduce waste (Singh and Kumar, 2024, Modarres and Ghalehnovi, 2024, Eghbali et al., 2019). Modern waste recycling techniques have attracted much attention due to limited landfill space and increased cost. Using specific amounts of recyclable wastes such as steel, polymers, and plastics in concrete mix designs has been considered in sustainable construction technology because it is cost-effective and has environmental benefits (Kedzierski et al., 2020). Low flexural and tensile strength is a key limitation of conventional concrete, but adding recycled fibers effectively enhances its mechanical performance(Cheraghi et al., 2023). Since the availability and efficiency of such additives depend on local resources, this study investigates accessible recycled materials in Kermanshah, Iran, to optimize both performance and cost.

Ali and Qureshi (2019) found that adding 0.5% glass fiber to concrete with 50% recycled coarse aggregate significantly improved mechanical properties. Lower fiber content (0.25%) also enhanced tensile and flexural strength, but higher amounts reduced durability. Overall, fiber addition improved tensile and flexural performance, though it could lower compressive strength. According to the results reported by Kizilkanat et al. (2015), using glass waste with the type of additives and colors weakens different levels of glass strength and combines with different polymers. Such variation in composition will disrupt inhibition. There are many techniques for recycling glass, one of which involves applying cement mortar as pozzolans. Benemaran et al. (2023) ound that using 100% recycled aggregates in concrete, along with 1–3% alkali-resistant glass fiber and 5–15% silica fume, improved strength. However, adding more than 2% fiber reduced performance. The optimal mix was 15% silica fume and 2% AR-GF, with the highest score (0.978) using TOPSIS analysis. Jalalinejad et al. (2023) found that glass powder improves fresh properties of concrete, with minor mechanical reduction at high replacement levels. Serin et al. (2023) investigate reusing concrete and ceramic waste in Hot Mix Asphalt (HMA) as fillers. Optimal bitumen content is determined, followed by tests on asphalt with different filler ratios: limestone, concrete waste, and ceramic waste. Concrete and ceramic waste show potential as effective HMA fillers, enhancing stability. Abed and Nemes (2019) examine waste material integration in self-compacting high-strength concrete (SCHSC). Replacing up to 50% natural aggregate with recycled concrete aggregate and up to 15% cement with waste fly ash or perlite powder enhances SCHSC's sustainability. Ojha et al. (2023) found slight improvement in fracture performance of recycled aggregate concrete compared to natural aggregate concrete. Kim and Jang (2022) investigate methods to mitigate the impact of adhered mortar on recycled aggregate concrete (RAC). They explore two removal techniques and highlight the importance of assessing adhered mortar content for improved RAC mix designs. Yıldırım and Özhan (2023b) assess glass fiber's impact on concrete under stress. Glass fibers improve strength, durability, and acid resistance, curbing stress-induced cracks. In high temperatures, glass fibers enhance strength retention, reinforcing concrete against external forces for increased durability and strength. Radhi et al. (2021) found waste glass and ceramics improve mechanical properties of reactive powder concrete, though higher replacement increases water absorption. Also, many other studies have examined the use of glass fibers (Gonçalves et al., 2022a, Tabatabaie Shourijeh et al., 2022, Gonçalves et al., 2022b). Studies have shown that incorporating recycled glass fibers from various waste sources can enhance the mechanical properties of concrete and composites, with notable improvements in tensile strength and material compatibility (Dehghan et al., 2017, Zhu et al., 2017, Mastali et al., 2017).

In recent years, the incorporation of recycled materials into concrete has gained attention as an effective strategy to enhance sustainability in the construction industry. Among these materials, waste plastics have shown potential due to their inert chemical nature, making them suitable as fillers or performance-enhancing additives in concrete mixtures. Studies have demonstrated that increasing the proportion of recycled plastic can improve both compressive and flexural strengths, with optimal results observed at approximately 30% replacement (Devi et al., 2024). Similarly, research on the use of recycled fine aggregates and powders indicates that, although their inclusion may reduce workability, they contribute to higher viscosity and a notable reduction in carbon emissions compared to conventional concrete (Guo et al., 2024). Furthermore, investigations into steel fiber-reinforced concrete made with recycled aggregates reveal that while recycled components can negatively impact tensile performance, the addition of 2% steel fibers significantly compensates for this reduction—enhancing uniaxial tensile strength by up to 69% and improving fracture energy up to 23 times relative to control specimens (Singh et al., 2023). Additional research exploring partial replacement of fine aggregates with recycled plastic, rubber, and glass has shown varied results. Glass improved both mechanical and durability properties, while plastic had moderate mechanical benefits but poor durability. Rubber, on the other hand, exhibited detrimental effects on both fronts (Steyn et al., 2021).

Ahmad and Chen (2020) showed that adding 10% silica fume and 0.5% basalt fiber to magnesium phosphate cement mortar improves water and high-temperature resistance by reducing porosity and increasing hydration. Yıldırım and Özhan (2023a) found that basalt fiber combined with mineral admixtures greatly enhanced mortar durability and strength at high temperatures. Yang et al. (2024) reported that thermally treated recycled glass fiber increases concrete's strength and impermeability, while Zhang et al. (2024) confirmed that optimal recycled glass fiber content improves the strength and workability of self-compacting recycled concrete.

Despite numerous studies on the use of recycled fibers and pozzolanic materials in concrete, significant research gaps remain regarding the combined effect of recycled glass fibers with various additives on the mechanical properties of concrete. Existing studies primarily focus on individual materials, while limited attention has been given to the interaction between glass fibers, microsilica, metakaolin, and nanosilica. Additionally, the influence of different fiber incorporation methods, such as pre-mixing and spraying, on the durability and long-term performance of concrete requires further investigation. Addressing these gaps can contribute to developing sustainable concrete mixtures with enhanced mechanical properties. In this study, the intensity of the influence of each additive on the key outcomes of the models was also evaluated based on the main effect plot diagrams. These plots identify the most influential model variables on the results.

2. Experimental study method

This section examines the materials used in concrete reinforced with recycled fibers (RFs) and glass waste, including microsilica (SF), metakaolin (MK), nanosilica (NS), and recycled glass fibers (Figure 1). Other components, such as cement, sand, water, and superplasticizer, were also used in the mix to determine the relative amounts of each material, both physically and chemically.

To evaluate the effects of recycled fibers and glass waste on the flexural and compressive strengths as well as the ductility of glass fiber reinforced concrete, alkali-resistant glass fibers with lengths of 20, 25, 30, and 40 mm were initially used in the preparation of reference specimens. Based on the results, it was observed that fiber length had no significant influence on the parameters studied and was not a determining factor. Therefore, glass fibers with a length of 25 mm were used in all specimens along with the corresponding pozzolanic materials. In a separate part of the study, the effect of different percentages of steel fibers on the behavior of concrete will be investigated. Glass fibers containing at least 16% zirconium in their composition are classified as alkali-resistant glass fibers.

The compressive strength of cylindrical specimens (150 mm diameter, 300 mm height) was evaluated according to the BS1881-203 standard using a standard uniaxial compression method. Tests were conducted at a constant loading speed of 0.2 to 0.4 MPa, after curing ages of 7 and 28 days, to assess both early and long-term strength development.

2.1. Recycled fibers

According to the methods of making recycled fibers /waste-reinforced concrete, these fibers are often used in concrete in two ways: the pre-mixing method and the spray method, respectively. The first method uses recycled fibers and waste as cut filaments. The second method transfers recycled fibers and waste to the spray gun as uncut filaments and then cuts them with the blade inside the gun. The glass fibers used in this study are shown in Figure 1.

Fig. 1 Concrete admixtures in this study

Alkali Resistant (AR) Glass Fibers with a length of 25 mm have been used in mixing designs to investigate the effect of recycled fibers and glass waste on flexural and compressive strengths and the ductility of glass fiber reinforced concrete. Alkali Resistant Glass Fibers are defined as glass fibers containing a zirconia content of about 16% mass (minimum percentage)(Kwan et al., 2018, Lipatov et al., 2015). Two types of recycled fibers and glass waste have been used to make concrete using pre-mixing and spraying. Tables 1 and 2 show the characteristics of this study's glass fibers.

Table 1 Specifications of glass fibers used in pre-mixing method

The desired characteristic	Amount
Type of fibers	AR-GLASS
The following percentage	More than 16 %
Specific weight (gr/cm^3)	2.8
Tensile strength (N/m^2)	1.5
Rupture strain	2 %
Modulus of elasticity (GPa)	75

Table 2 Specifications of glass fiber used in spray method

Characteristic	Glass fiber
Type of fibers	AR-GLASS
Diameter of filaments (mμ)	16
Strain at the yield point	2.4 %
Bulk density of fibers (TEX)	2390
Final resistance (N/TEX)	0.5

Modulus of elasticity (N/TEX)	50.4
Specific weight (gr/m3)	2.7
Percentage of zirconium	16.7
Moisture content	0.072

2.2 Mixing design

The present study has investigated the effect of using different percentages of recycled fibers and waste in the glass industry in specimens containing SF, MK, and NS. Also, the present study has investigated the effect of pre-mixing and spray methods in making reinforced concrete with recycled fibers and glass industry waste on the concrete's mechanical properties. Recycled fibers/waste-reinforced concrete and cement concrete, with a relatively low water-to-cement ratio, were utilized in this study. Based on the manufacturing method, the optimal water-to-cement ratio ranges from 0.33 to 0.35, while the sand-to-cement ratio is typically between 0.75 and 1.

Fig. 2 Compressive testing of samples

For the concrete mixing plant used in both pre-mixing and spray methods, the standard mixing method of the regulations ACI Committee (2005) has been used. Table 3 lists the materials used in pre-mixing concrete mixing designs. The amounts of fibers, Superplasticizers (SP), NS, MK, and SF are listed in the weight percentage of cement. Table 4 shows the amounts of materials used in the sprayed concrete mixing designs. These values are provided in terms of weight percentages of the materials included in the mixtures, including sand, cement, superplasticizer (SP), nanosilica (NS), metakaolin (MK), microsilica (SF), fibers, and water. PC in these tables stands for Plain Concrete, which refers to concrete without any additives, as shown in the provided mixing designs.

Table 3 The amounts of materials in pre-mixing concrete mixing designs

Symbol	Sand (kg)	Cement (kg)	SP	NS	MK	SF	Fiber	Water (Liter)
PC	939.1	939.1	1	0	0	0	0	326.7
GF1.5	927.6	927.6	1	0	0	0	1.5	324.7
GF2.5	920.0	920.0	1	0	0	0	2.5	322.0
GF1.5-SF10	917.5	834.1	1	0	0	10	1.5	321.1
GF1.5-SF15	913.2	794.1	1	0	0	15	1.5	319.6
GF1.5-MK10	915.7	932.4	1	0	10	0	1.5	320.5
GF1.5-MK15	908.2	797.7	1	0	15	0	1.5	317.9
GF1.5-NS0.75	926.8	919.9	1	0.75	0	0	1.5	324.4
GF1.5-NS1.5	929.0	912.3	1	1.5	0	0	1.5	324.1
GF2.5-SF10	910.0	827.3	1	0	0	10	2.5	318.5
GF2.5-SF15	905.7	787.6	1	0	0	15	2.5	317.0
GF2.5-MK10	908.2	825.6	1	0	10	0	2.5	317.9
GF2.5-MK15	900.7	783.2	1	0	15	0	2.5	315.3
GF2.5-NS0.75	919.9	912.3	1	0.75	0	0	2.5	321.7
GF2.5-NS1.5	918.8	904.8	1	1.5	0	0	2.5	321.4

Table 4 Amounts of materials used in sprayed concrete mixing designs

Symbol	Sand	Cement	SP	NS	MK	SF	Fiber	Water
PC	908.59	908.6	1	0	0	0	4.04	318
GF1.5	893.35	893.35	1	0	0	0	5.72	312.67
GF2.5	898.7	817	1	0	0	10	4.7	314.54
GF1.5-SF10	894.46	777.8	1	0	0	15	4.12	313.06
GF1.5-SF15	896.9	815.35	1	0	10	0	4.29	313.91
GF1.5-MK10	889.53	773.51	1	0	15	0	4.5	311.34
GF1.5-MK15	907.77	901.01	1	0.75	0	0	4.6	317.72
GF1.5-NS0.75	906.97	893.56	1	1.5	0	0	4.7	317.44
GF1.5-NS1.5	883.63	803.3	1	0	0	10	5.8	309.27
GF2.5-SF10	879.46	764.7	1	0	0	15	5.6	307.81
GF2.5-SF15	881.8	801.68	1	0	10	0	5.9	308.64
GF2.5-MK10	847.2	460.5	1	0	15	0	6	306.12
GF2.5-MK15	982.55	885.9	1	0.75	0	0	6	312.4
GF2.5-NS0.75	981.76	878.58	1	1.5	0	0	6.1	312.11
GF2.5-NS1.5	908.59	908.6	1	0	0	0	4.04	318

2.3 Removing specimens from the molds and curing the specimens

After the specimens were created, they were placed in molds and kept in a humid environment for 24 hours to cure (Prem et al., 2013). Once the curing was complete, the specimens were removed from the molds and put in a curing basin (Figure 3).

Fig. 3 Curing the 28-day specimens under moisture

They were submerged in the water basin for 28 days and then transferred to a tank with a relative humidity of 70-65% to examine the flexural behavior of 90 days of glass fiber-reinforced concrete.

2.4 Test setup for the bending test

The bending test is performed according to BS-EN1170 (British Standard) and ASTM C78 (2010) standards by a four-point bending machine (Figure 4). Rectangular beams with dimensions of 100 mm in width (b), 100 mm in depth (d), and 400 mm in length (L) were cast for the bending test. After the standard curing period, the beams were tested using a four-point bending machine with a 50 kN capacity. In this method, the samples are placed on two cylindrical supports. In this condition, the distance between the end of the sample and the adjacent support is 25 mm. According to the proposal of the ASTM C1018 standard (211, 2005), the loading speed is considered to be 0.1 mm/min. Similarly, Eq. (1) was used to calculate the modulus of rupture (MOR). In this equation, b, d, and L represent the sample's width, height, and length, respectively.

$$MOR = \frac{FL}{bd^2} \tag{1}$$

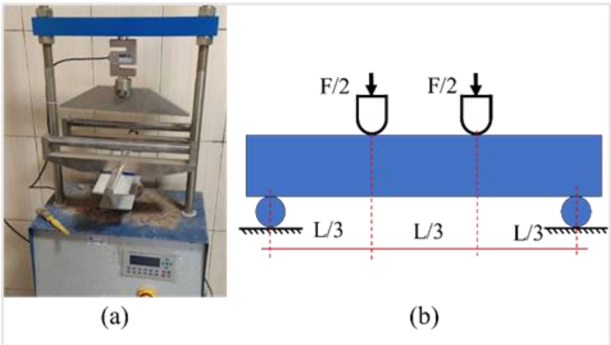

Fig. 4 (a) Four-point bending device (b) Schematic of the sample under 4-point loading

3 Experimental results

The study investigated the influence of using different percentages of recycled fibers, glass waste, and pozzolanic materials on the mechanical properties of concrete reinforced with recycled fibers and glass waste. This section presents the results of the behavior of various specimens concerning their compressive strength and flexural strength.

3.1 The results of compressive strength

Compressive strength is a key parameter in evaluating the mechanical performance of concrete. In this study, standard uniaxial compression tests were conducted on cylindrical specimens to assess the strength development at different curing ages. The results provide insights into both early-age and long-term strength characteristics, which are essential for understanding the material's structural performance. In this study, approximate equations were proposed to estimate the experimental results. These equations were derived using curve-fitting techniques based on experimental data and were formulated to minimize the difference between their predictions and the experimental results. One advantage of these equations is the continuity of their output, unlike the discrete nature of experimental results.

Figures 5a and 5b show the effect of the type and amount of pozzolanic materials used on the 7-day and 28-day compressive strength (CS) of reinforced samples with 1.5% and 2.5% recycled fibers and recycled glass waste. The vertical axis on the right shows the values normalized to 7-day PC in these figures. It can be seen that the results for the 7-day samples, the models containing SF and MK (GF-SF10, GF-SF15, GF-MK10, GF-MK15), demonstrate higher values than the GF model. Specifically, the GF-SF10 and GF-SF15 models showed an average increase of 8% and 14%, respectively, compared to the GF model, while the GF-MK10 and GF-MK15 models exhibited average increases of 19% and 30%, respectively. The 7-day and 28-day results indicate that the GF-MK15 model demonstrated an average increase of 8% and 17%, respectively, compared to the PC model. These models exhibited the highest performance among all mixtures at both 7-day and 28-day curing periods. The GF-MK10 model showed lower results than the PC model at the 7-day curing period; however, over time and by reaching 28 days, it achieved 10% higher results compared to the PC model.

$$CS = 6NS + 58MK - 0.02SF - 0.38GF + 0.4(day) - 0.01GF(day) - 3GF \times NS + 14MK \times GF + 22GF \times SF + 37 \quad (2)$$

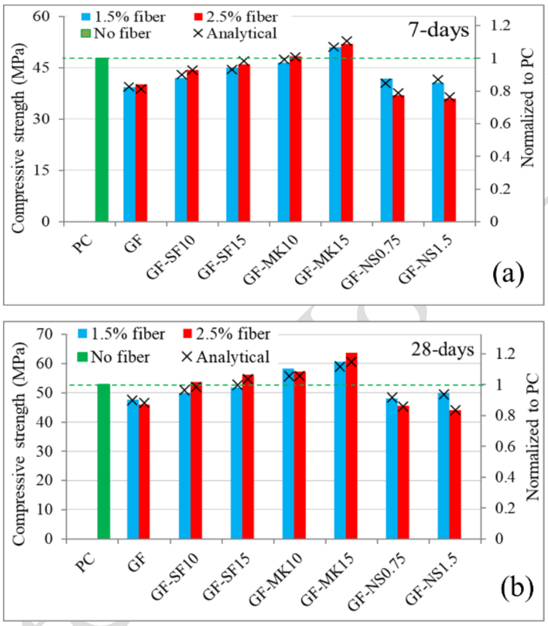

Fig. 5 Impact of pozzolanic materials on compressive strength: (a) 1.5% recycled fibers, (b) 2.5% recycled fibers and glass waste

These results are valid for both GF=1.5% and GF=2.5% cases. In this figure, the models with positive values indicate higher results compared to the PC. As observed, under the 7-day condition, only the MK 15% model (GF-MK15) exhibits positive values. In the 28-day samples (Figure 5b), the models containing SF and MK had more results than the GF sample. Additionally, the models with GF=2.5% containing SF and MK had more results than the PC sample. Eq. (2) was presented using the curve fitting technique to estimate the compressive strength of the samples. The results of this equation and the laboratory results are presented in Figure 5, which shows that they are closely matched with acceptable accuracy. It should be noted that the parameters of this equation must be substituted in terms of a percentage.

Comparing samples with and without pozzolanic materials, the 28-day compressive strength of concrete reinforced with recycled fibers and glass waste increased when pozzolanic materials were used. The formation of cement paste and the reaction of pozzolanic materials with calcium hydroxide in concrete may be the causes of this. Concrete becomes denser due to increased paste production, which lowers calcium hydroxide and boosts compressive strength. Due to the reduction of concrete performance in the presence of glass fibers and the severe decrease in concrete performance due to nanosilica, the compressive strength of designs containing 2.5% recycled fibers and glass and nanosilica wastes has decreased significantly. This is due to the non-uniform dispersion of recycled fibers, waste glass, and nanosilica on the concrete surface.

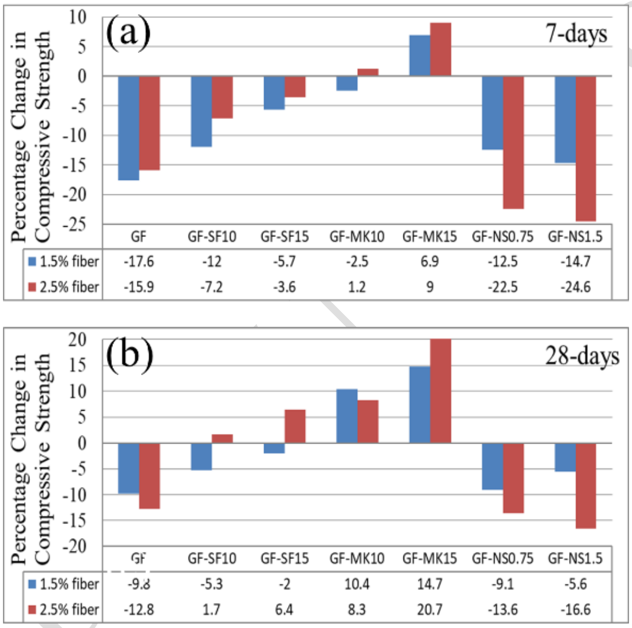

Fig. 6 The decrease in the compressive strength of the samples compared to PC (a) 7 days (b)28 days

Figure 6 presents an evaluation of the reduction or increase in compressive strength of the samples in comparison to PC. The results show that the model containing 1.5% NS had the highest decrease in compressive strength for both 7 and 28-day samples. On the other hand, the sample containing 15% MK had the highest increase in compressive strength for both 7 and 28-day samples.

Figures 7 and 8 present the modulus of rupture results of the models. The difference between these figures lies in the GF percentage in the concrete. As shown in these two figures, the modulus of rupture decreases in glass fiber-reinforced specimens from 7 days to 28 days and from 28 to 90 days. The results indicate that increasing the percentage of microsilica and metakaolin from 10% to 15% increases the modulus of rupture. On the other hand, the addition of nanosilica has led to a decrease in all samples. The models containing 4% and 6% recycled fibers and glass waste along with nanosilica, such as GF-NS0.75 and GF-NS1.5, exhibited a lower modulus of rupture compared to other models. This can be attributed to the clumping of nanoparticles, which negatively affects the distribution and bonding of the fibers. The reduction in the modulus of rupture with increasing submerged days is mainly attributed to the denser and more brittle nature of the cementitious composite over time, which diminishes the fiber–cement interaction. Additionally, prolonged submersion negatively affects the bond between recycled fibers and the cement-based material, leading to reduced flexural strength

Eq. (3) has been presented using the curve fitting method to estimate the modulus of rupture results. This equation allows for an accurate estimation of the modulus of rupture based on the samples' variables and the day of testing. The accuracy of the results obtained through this equation is acceptable, as shown in Figures 6 and 7, which show that they are close to the laboratory results.

$$\mathrm{MOR} = \mathrm{NS} + 11\mathrm{MK} + 10\mathrm{SF} + 6\mathrm{GF}^{0.57} - 0.88\,\mathrm{GF} \times \mathrm{NS} + 2.6\,\mathrm{GF} \times (\mathrm{day})^{0.253} \quad (3)$$

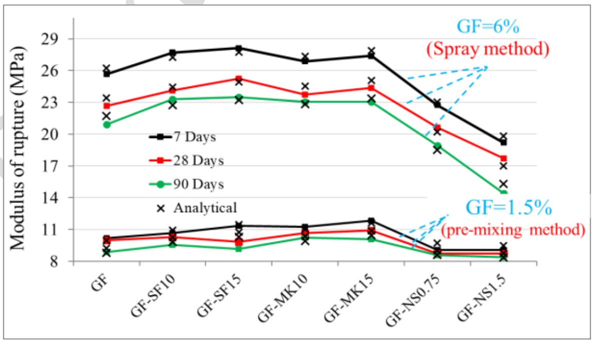

Fig. 7 The effect of model variables on the modulus of rupture for models with GF=1.5% and GF=6%

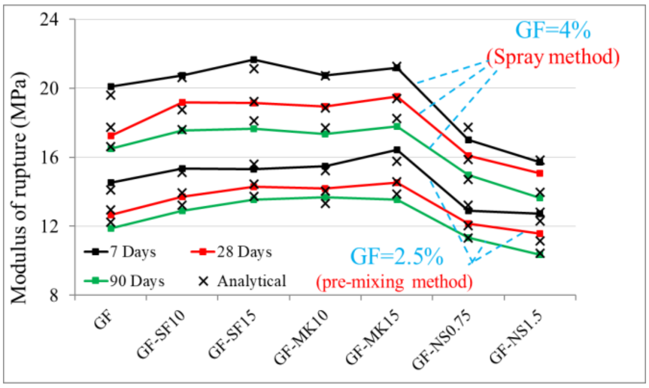

Fig. 8 The effect of model variables on the modulus of rupture for models with GF=2.5% and GF=4%

The modulus of rupture improved in the samples reinforced with recycled fibers and glass waste compared to the samples without fibers because the recycled fibers and glass waste increase the tensile strength of concrete and create a bridge between the cracks, preventing their growth due to the applied loads.

By comparing the modulus of rupture of the mixing designs containing glass fibers, it can be seen that the modulus of rupture decreases with the use of more of these fibers. This is because, with the increase of glass fibers, the efficiency of concrete decreases, and in this condition, cement mortar loses its integrity.

3.2 Ability to bear load after cracking

One of the essential parameters of concrete is the ability to bear the load after cracking (BLAC), which is investigated in this section. The BLAC parameter was determined by evaluating the load-bearing capacity increase after the initiation of the first crack in the specimen. Figure 9 shows the effect of model variables on this parameter. According to these diagrams, the specimens made by the spray method (GF=4% and GF=6%) have a higher tolerance against the loads after cracking than those made by the pre-mixing method. It should be noted that the specimens with GF=4% and GF=6% were made using the spray method, while those with GF=2.5% and GF=1.5% were produced using the pre-mixing method. These results in both pre-mix and spray methods show that the residual strength after cracking has increased with increasing recycled fibers and glass waste. This improvement can be attributed to the close spacing of fibers, which effectively inhibits the propagation of microcracks. Furthermore, the fibers delay the initiation of tensile cracks, thereby enhancing the post-cracking load-bearing capacity. After cracking, adding microsilica increased the load-bearing capacity in reinforced concrete. However, the addition of nanosilica and metakaolin decreased the results in all samples. Eq. (4) was presented using the curve fitting method to estimate the results. This equation is based on the experimental results. The coefficients of the variables in the equation were calculated in such a way that the difference with the experimental results is minimized. Figure 9 also shows a comparison between the experimental results and the results predicted based on Eq. (4). It can be seen that they are close to each other with acceptable accuracy.

$$\mathrm{BLAC} = -11.7\mathrm{NS} + 30\mathrm{MK} - 58\mathrm{SF} + 22.55\mathrm{GF} - 0.215(\mathrm{day}) + 30\mathrm{MK} \times \mathrm{GF} - 0.27\mathrm{NS} \times \mathrm{GF} - 0.0022\mathrm{GF} \times (\mathrm{day}) \tag{4}$$

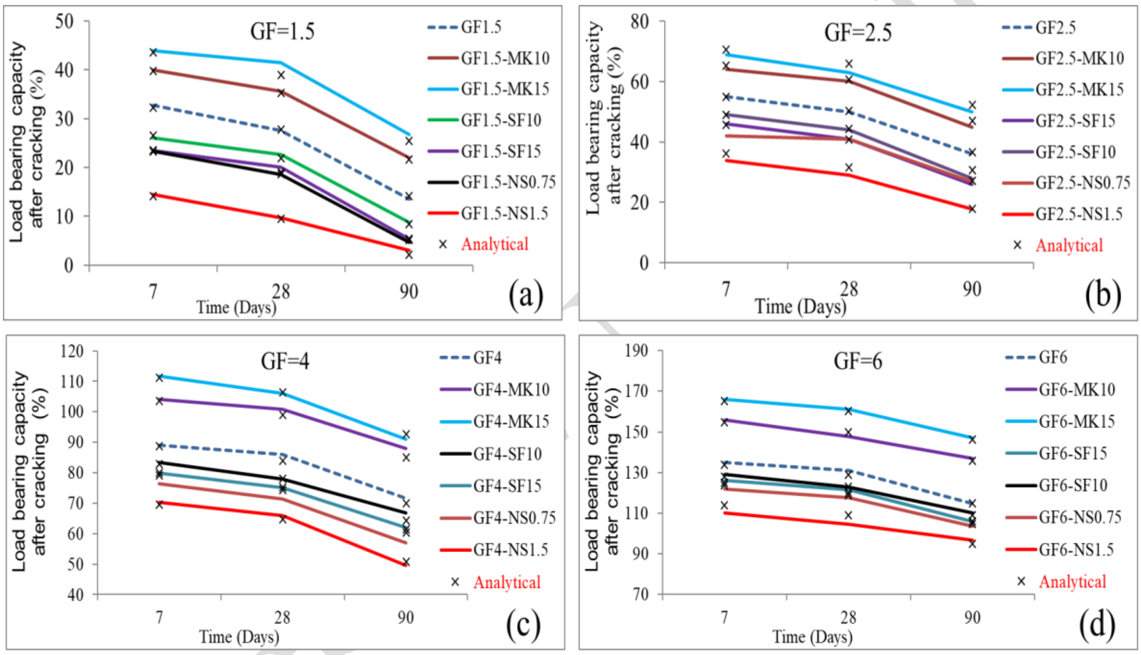

Fig. 9 Load bearing capacity after cracking: (a) GF=1.5%, (b) GF=2.5%, (c) GF=4%, (d) GF=6%

In some cases, it was observed that the cracks in samples reinforced with glass fibers moved in the longitudinal direction, leading to their breakage. Fig. 10 illustrates the failure mode of specimens reinforced with 6% recycled fibers, glass waste, and nanosilica.

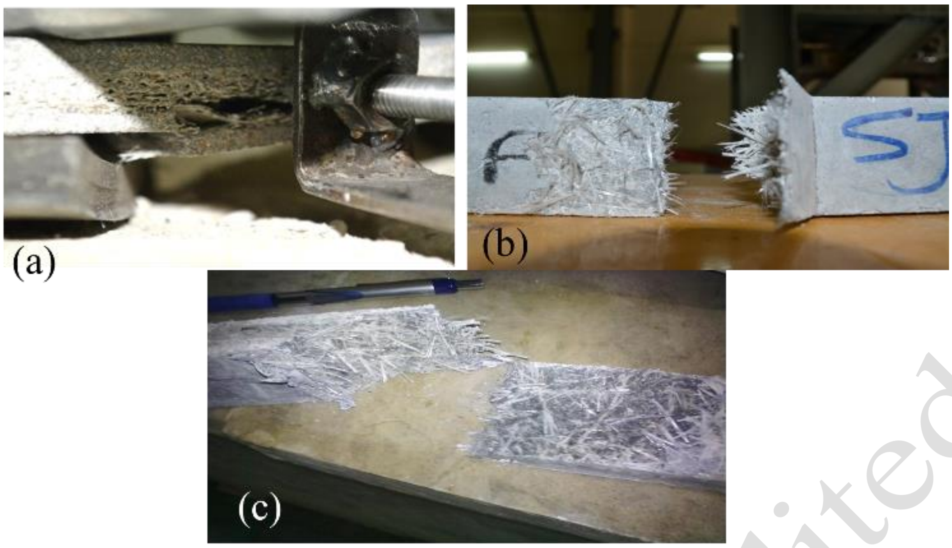

Fig. 10 The failure mode of samples reinforced with 6% recycled (a)fibers, (b)glass waste, and (c) nanosilica

The experimental results demonstrate that varying percentages of recycled fibers and glass waste significantly affect the mechanical properties of concrete. Specifically, increasing the recycled fiber content led to a noticeable reduction in compressive strength, particularly evident in the 7-day tests compared to the 28-day tests. Conversely, although the addition of glass waste slightly reduced compressive strength, it substantially enhanced the modulus of rupture and the load-bearing capacity after cracking, indicating improved flexural performance. Furthermore, incorporating pozzolanic materials such as metakaolin and microsilica helped to counteract the decrease in compressive strength, ultimately achieving a more balanced performance. These findings underscore a trade-off between early strength and ductility, suggesting that an optimized combination of recycled fibers, glass waste, and additives can yield sustainable and resilient concrete formulations.

In certain instances, it was observed that the glass fiber-reinforced samples broke because the cracks propagated along the samples' longitudinal axis. The reason for this could be that concrete becomes less efficient when the quantity of glass fibers used in it increases. Concrete will function much less efficiently if many recycled fibers, glass waste, and pozzolanic materials like nanosilica are used. By reducing the efficiency of concrete, it will not be possible to distribute the fibers uniformly on the surface of the concrete. In this situation, due to the accumulation of recycled fibers and glass waste in one point of concrete and the lack of a suitable coating of mortar around the fibers, cracks are formed at the location of these fibers and cause the concrete to break. As a result, it becomes challenging to distribute fibers uniformly on the surface of the concrete. This leads to accumulated recycled fibers and glass waste in one concrete point, creating cracks due to the lack of a suitable mortar coating around the fibers. Figure 10 provides examples of this type of rupture in concrete reinforced with recycled fibers and glass waste.

Based on the experimental results, the addition of recycled fibers and glass waste influences the concrete's mechanical behavior in several notable ways. The 7-day compressive strength tests show a more significant reduction with increased recycled fiber content compared to the 28-day tests, indicating that while early-age strength is compromised, the long-term performance benefits from continued hydration and pozzolanic reactions. In contrast, although the incorporation of glass waste slightly decreases compressive strength, it markedly enhances the modulus of rupture and load-bearing capacity after cracking, demonstrating improved ductility and crack-bridging capabilities. Furthermore, the integration of pozzolanic materials such as microsilica and metakaolin not only compensates for the decrease in compressive strength but also contributes to a denser and more resilient matrix. These findings underscore the need for a balanced approach in optimizing the proportions of recycled fibers, glass waste, and additives to achieve sustainable concrete formulations with both adequate strength and improved durability.

To verify the accuracy of the proposed approximate Eqs. (2-4), the mean absolute percentage error (MAPE) was calculated using Eq. (5) (Cheraghi et al., 2024a), and the results are presented in Table 5. In this equation, *N* represents the total number of laboratory tests. The results indicate that the MAPE of all calculations is less than 3%, which suggests that the presented equations are accurate and reliable (Cheraghi *et al.*, 2024a).

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|Exp._{res_i} - \mathrm{Ana.}_{\mathrm{res}_i}|}{Exp._{res_i}}\right) \tag{5}$$

Table 5 The MAPE value of the proposed equations.

Results	MAPE (%)
Compressive strength	1.67

Modulus of rupture	2.22
Load bearing capacity after cracking	2.08

3.3 Comparison of the effect of each of the variables of the samples

In the previous sections, it was observed that each of the variables of the samples had a different effect on the results. For this reason, it is essential to identify the variables that have the least and the most impact on the results. In the same way, the Main Effect Plot was presented in the form of Figure 11. As can be seen, these diagrams are presented for compressive strength, modulus of rupture, and load-bearing capacity after cracking. There are two important points in these diagrams. If the slopes of the lines were positively trigonometric, it means that as the variable increases, the results also increase (Cheraghi et al., 2024b, Ryan et al., 2012). Also, the higher the slope of the lines, the more significant the impact of that variable on the result.

GF is the most influential variable on the results of the modulus of rupture and load-bearing capacity after cracking, as its slope in these two results is greater than that of the other variables. The variables day and NS have an inverse effect on the results of the modulus of rupture and load-bearing capacity after cracking. The variables Day, MK, and SF have a positive effect on the compressive strength. The variables MK, SF, and GF have a positive impact on the modulus of rupture. Furthermore, the variables MK and GF have a positive effect on the load-bearing capacity after cracking.

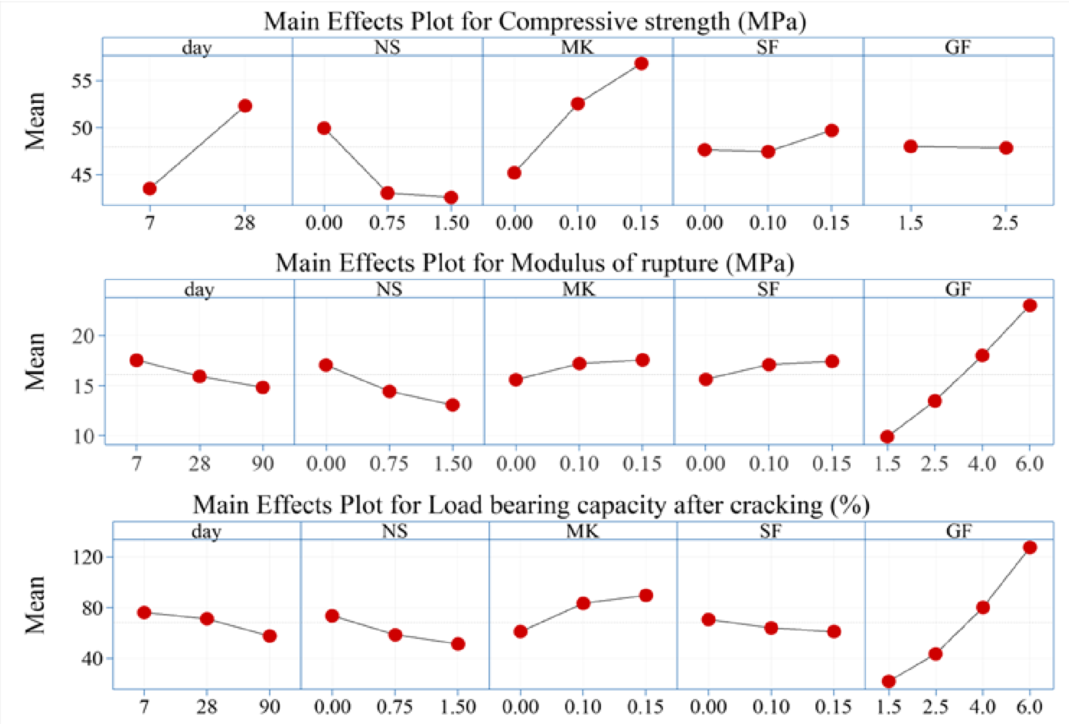

Fig. 11 Main effect plots for compressive strength, modulus of rupture, and load-bearing capacity after cracking

4 Conclusion

This study aimed to investigate the effect of varying percentages of recycled fibers and recycled glass waste on the compressive strength, modulus of rupture, and load-bearing capacity after cracking of reinforced concrete containing these recycled fibers and glass waste. Different combinations of recycled materials, including microsilica, metakaolin, and glass fibers, were tested under controlled laboratory conditions. Approximate equations were developed to predict compressive strength, modulus of rupture, and load-bearing capacity, showing good agreement with experimental results. The study also identified microsilica (MK) and glass fibers (GF) as the most influential variables affecting concrete performance. The results of this research are summarized in the following paragraphs:

- The addition of recycled fibers and glass waste reduced the compressive strength of concrete. The reduction rate was higher in 7-day samples than in 28-day samples. Furthermore, the compressive strength decreased even further with an increase in fibers. In particular, the sample containing 2.5% fibers exhibited a reduction in compressive strength of 16.75% and 11.3% in 7-day and 28-day samples, respectively, when compared to the sample without fibers.

- Samples containing 15% MK displayed the highest compressive strength. Specifically, GF2.5-MK15 samples exhibited a 9% and 20.7% higher compressive strength than the reference sample after 7 and 28 days, respectively. The addition of SF to the samples resulted in an increased compressive strength. Adding 10% and 15% SF increased the average compressive strength by 12% after 7 and 28 days.
- The results of the modulus of rupture test indicate that increasing the percentage of microsilica and metakaolin from 10% to 15% increases the strength of the material. However, the addition of nanosilica has resulted in a decrease in strength in all the samples. Also, with the increase of GF, the modulus of rupture of the sample increased. So, the highest modulus of rupture related to the model had 6% GF and 15% SF.
- The approximate equations developed in this study for estimating compressive strength, modulus of rupture, and post-cracking load-bearing capacity showed good agreement with experimental data and can be utilized as practical tools in real-world design applications.
- As the age of the sample increases, the load-bearing capacity decreases, as revealed by the test results conducted after cracking. The models that contain MK show an increase in the load-bearing capacity, whereas other variables have a negative impact on this parameter compared to the reference model.
- To calculate the compressive strength, modulus of rupture, and load-bearing capacity after cracking, approximate equations were presented based on the curve fitting method, which was in good agreement with the experimental results and can be used to calculate these parameters.
- The most influential variables on compressive strength, modulus of rupture, and ability to withstand load after cracking were MK, GF, and GF, respectively. GF variable had the least effect on compressive strength.

5 Recommendations for future study

Following the completion of this research, the subsequent paragraphs will present recommendations for future studies.

- In order to evaluate the effectiveness of concrete under difficult circumstances, it is imperative to conduct a thorough assessment of its performance.

- The creep and dry shrinkage properties of glass fiber-reinforced concrete are not well-documented, leading to a lack of data on these important characteristics.
- Further investigation into the use of recycled glass fibers at higher percentages could help identify the optimal balance between sustainability and mechanical performance. Additionally, exploring the impact of different fiber lengths and orientations on concrete properties may provide valuable insights for improving concrete mix designs.
- Further research using pozzolanic materials to improve the compressive capacity of glass fiber-reinforced concrete is necessary.
- Future research should focus on assessing the long-term performance of these mixtures under real-world environmental conditions, such as varying temperatures and humidity. Additionally, optimizing the fiber content and dispersion could improve the overall mechanical performance of the concrete.
- One limitation of this study was the exclusive use of a single type and geometry of recycled glass fiber, which may affect the generalizability of the findings. Furthermore, although standardized laboratory conditions were maintained throughout the experiments, real environmental factors, such as temperature fluctuations and humidity variations were not simulated. These aspects could influence the long-term performance of fiber-reinforced concrete and are recommended for further investigation in future studies.

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