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Mechanical Properties of Engineered Cementitious Composites with Low Cost Fibers and Recycled Glass Filler

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Abstract: The work presented in this article attempts to evaluate the effect of partial and full substitution of silica sand by fine recycled waste glass (RG) in M45 engineered cementitious composites. Two groups with a total of eight mixtures were prepared with 2% or without untreated polyvinyl alcohol (PVA) fibers. Each group included four mixtures with RG substitution ratios of 0, 30, 60, and 100%. The compressive strength and flexural strength of all mixtures were tested at ages of 7, 28, and 90 days. The test results showed that the influence of RG was different for plain specimens from those with PVA fibers. For plain specimens, the incorporation of RG mostly increased the compressive and flexural strength at mature ages of 28 and 90 days, while this positive effect was not the trend at 7 days of age. On the other hand, the incorporation of RG had in most cases a negative impact on the compressive and flexural strength of specimens reinforced with short untreated PVA fibers.

Keywords: recycled glass; waste glass aggregate; ECC; low cost PVA; compressive strength; flexural strength

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1. Introduction

Global warming and excessive depletion of natural resources are the major human life threats within the next few decades. The global economy growth is not costless, where the slow poisoning of air and water is a sort of rebound of our daily life trends. Humanity now feels the danger and impact of accelerated climate change due to the enormous carbon dioxide emissions that facilitate daily life needs and the century's way of living. A large number of research efforts are being implemented at the aim of finding possible solutions to decelerate the reversed effects of our high-consumption lifestyle. Sustainability is now the main focus to reduce the environmental cost of harmful but essential productions that release significant quantities of CO_2 to the atmosphere [1]. Among the main pollutant sectors is the construction industry, where cement and steel factories are responsible for billions of tons of carbon oxide emissions every year. In recent decades, several industry byproducts that have pozzolanic minerals, such as fly ash, silica fume, and furnace slag were utilized to be candidate partial or full substitutions of Portland cement [2]. Notably, to manufacture each 1 ton of cement, approximately 0.7 ton of CO_2 is released to the atmosphere [3]. This trend of substitution would be a helpful step toward a more sustainable construction industry. On the other hand, the reuse of byproducts would be a dual greening process when considering the required landfilling efforts of these materials and their negative effects on the quality of lands, ground water, and thus on human health. Meanwhile, the research efforts of other works were directed on utilizing other industry and municipal waste materials, such as rubber and glass, as aggregate substitutions. This opportunity would have a two-fold positive environmental and economic impact, where on the one hand, reusing and recycling of waste materials would reduce the efforts, costs, and environmental impact of their landfilling, while on the other hand, this would slow down the accelerated depletion of Earth's natural resources.

One of the most common daily used materials is glass, which is a basic material to produce many disposable and non-disposable products. Examples are liquid bottles and other shapes of glass containers, windows, screens, as well as many other parts of electronics, medical devices, and tools [4]. Considering the daily large municipal recycled waste glass (RG) output, the landfilling of these wastes is another daily ecological and economical challenge despite the fact that RG is 100% recyclable [4], where the recycling rate in some countries is noticeably low [5]. However, other countries, such as Australia, reported encouraging recycling percentages reaching approximately 60% in recent years [6]. Nevertheless, large amounts are still being landfilled causing serious waste management issues [7]. One of the potential recycling uses of RG is the incorporation as a substitution construction material. RG has already been utilized in concrete production as coarse aggregate, fine aggregate, or cementitious material [8].

A large number of literature is available on the reuse of waste RG as a partial or full substitution of cement or aggregate in different types of concrete. Most of the available literature on using RG powder as a partial replacement of Portland cement revealed a strength decrease with RG content increase [9–20]. However, there is no wide agreement when RG is utilized as a filler. In previous studies, where the mixture fine aggregate was partially or fully replaced with RG particles, lower density, higher bleeding, and segregation issues were reported [21], while different results are valid regarding the effect of aggregate RG on concrete strength [7,21]. Some studies reported gradual strength gain with the increase in RG aggregate replacement ratio [22,23], while others reported strength developments up to a specific RG replacement ratio followed by strength decline with the increase in RG aggregate content [24–26]. On the other hand, some other studies showed that RG aggregate has a minor effect or leads to decreased strength [27–30]. The size of the RG aggregate was different from one study to another. Some studies used RG as a coarse aggregate with maximum particle sizes larger than 5 mm [31–33] or even larger than 14 mm [27,34,35]. These studies agreed that the use of RG as coarse aggregate decreases the compressive and tensile strength and reduces the workability. However, RG fine aggregate with a maximum particle size of approximately 5 mm was the most frequently investigated [22,25,28,36,37], while fine aggregate with maximum particle sizes between 1.18 and 4 mm were considered in other studies [29,38–41]. Reviewing the available literature, it can be summarized that a very fine RG aggregate has mostly a positive or neutral impact on the strength, while there is no agreement regarding the influence of larger RG aggregate particles [42].

Engineered cementitious composites (ECCs) are one of many new superior fibrous concrete mixtures that were developed during the last few decades. ECC is known for its ability to absorb significantly higher tensile strains compared to conventional fibrous concrete [43]. However, ECC includes large amounts of binder in addition to polyvinyl alcohol fibers (PVA), which in turn is considered as a major shortening where the environmental impact and cost are exaggerated compared to fibrous concrete. Therefore, many studies investigated the possibility of having ECC with comparable strain capacity and ductility, but with lower environmental impact by incorporating higher fly ash contents rather than cement [44–46], where fly ash/Portland cement ratios of 2.2 [47,48] and even up to 2.8 [49,50] were tested. Other investigators tried other supplementary binders, such as furnace slag [51,52], silica fume [53], rice husk ash [54,55], or iron tore tailings [56] to produce greener ECC mixtures. On the other hand, some previous investigators tested some waste materials or byproducts, such as rice husk ash [54,55], iron ore tailings [57,58], and hollow glass microspheres [59,60] as a filler material in ECC.

The reviewed literature showed that RG was incorporated as a replacement of cement or as coarse or fine aggregate in different types of concrete. Moreover, it reveals that several supplementary industry byproducts that have pozzolanic activity were tested toward producing a greener ECC. However, only a very limited number of studies tried the use of RG powder in ECC, most of which utilized RG powder as fly ash replacement [61–65], while to the best of the authors' research, only a single previous study attempted to use RG as a filler in ECC [66,67], where rounded glass powder with 100 to 300 µm in grain size was utilized in combination with high fly ash/cement content of 2.2 and coated PVA fibers. The limited research on this topic imposes the need for further studies to explore the effect of RG as a supplementary filler material. Therefore, the work presented in this study was directed to investigate the influence of using RG as a partial and full replacement of silica sand in the basic M45 ECC mixture on the mechanical properties of the mixture. Mixtures with different RG/silica sand substitution ratios and with or without low cost uncoated PVA fibers were prepared and tested in this study.

2. Materials and Methods

2.1. Materials and Mixtures

Engineered cementitious composite mixtures were prepared and tested in this study following the M45 ECC mixture introduced by Li [43]. The basic M45 ECC mixture incorporates 570 kg/m^3 of cement with a 1.2 fly ash/cement ratio and 0.8 silica sand/cement ratio. The water/total binder ratio of this mixture is 0.27, which is used with a small amount of high range water reducers. Surface-treated PVA fibers are typically used in this mixture at a volumetric content of 2%. The same mixture was used in this study but with low cost surface-untreated PVA rather than the typical high cost surface-treated PVA. The second difference is the utilization of recycled waste glass fine aggregate (RG) as a replacement of the typical silica sand, either partially or totally, where 0, 30, 60, and 100% of the silica sand was replaced by RG composing four different mixtures with four replacement ratios. To evaluate the combined effect of fiber type and RG replacement ratio, two groups of mixtures were cast. Each of the two groups included four mixtures with the identification initial RG, which refers to the RG replacement ratio, and one of the middle numbers 0, 3, 6, or 10 that refers to the RG replacement ratios of 0, 30, 60, and 100%, respectively. The last section of all of the four mixtures is the same for each group, which identifies the used fiber type. The first group ends with F0, which refers to the group of the reference plain mixtures that include no fibers, while the mixtures of the second group end with the section PVA referring to the used PVA fibers, as detailed in Table 1.

Table 1. RG replacement percentage and fiber details of the eight mixtures.

Mixture	% Replacement of RG	% Fiber
RG0F0	0	0
RG3F0	30	
RG6F0	60	
RG10F0	100	
RG0PVA	0	2.0
RG3PVA	30	
RG6PVA	60	
RG10PVA	100	

RG = Recycled glass fine aggregate; F0 = No fiber; PVA = Polyvinyl alcohol fiber.

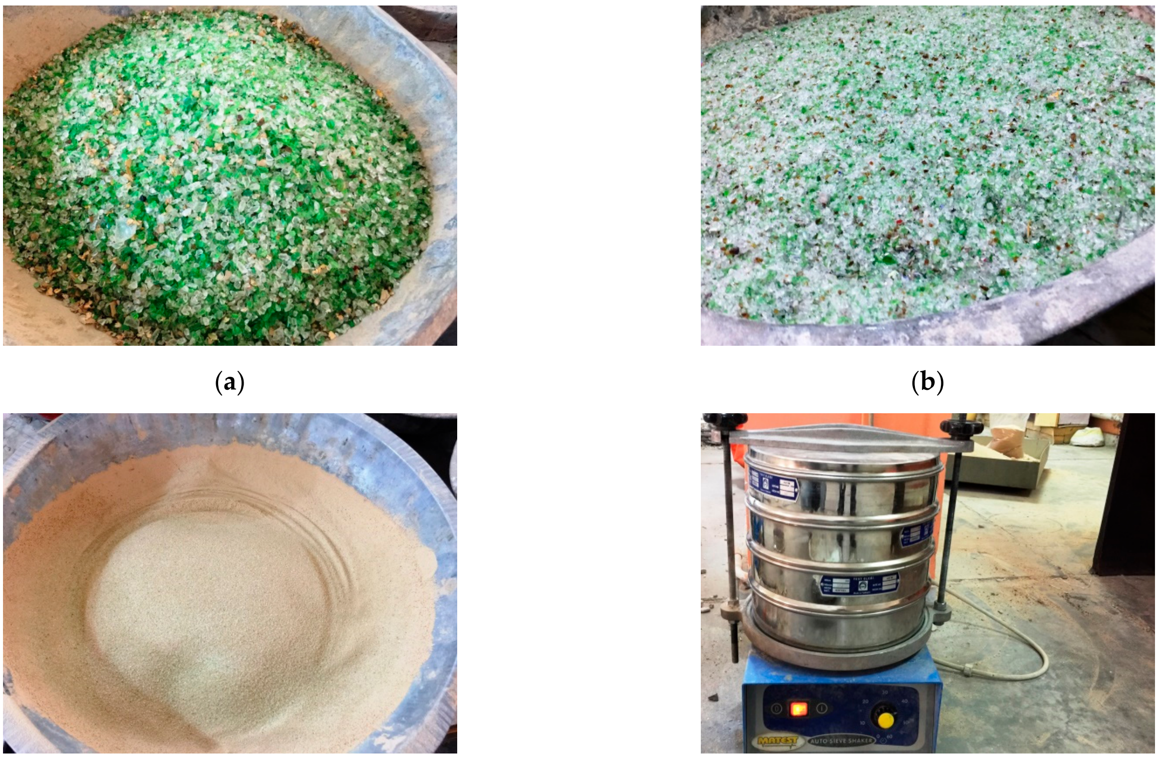
The used cement was class 42.5R Portland cement produced by the local factory Mass in the north region of Iraq. Type F fly ash was used as a secondary binding material and was produced by Sika. The specific gravities of the cement and fly ash were 3.15 and 2.24 kg/m^3, respectively, while the specific areas of the used cement and fly ash were 362 and 360 m^2/kg, respectively. The properties of the PVA fibers are listed in Table 2, while their appearance is shown in Figure 1. The used silica sand was provided by Sika and its appearance is shown in Figure 1 with a grain size range of 80 to 200 µm. The liquid state ViscoCrete 5920-L, produced by Sika, was used as a high range water reducer at a constant dosage of 4.9 kg/m^2 for the 12 mixtures. Finally, the recycled glass fine aggregate was prepared in the laboratory using the Los Angeles abrasion machine and a fine grinding machine following the steps described in Figure 2, where after the manual crushing of the collected waste glass bottles (Figure 2a), the crushed small particles were placed in the Los Angeles machine for finer crushing as shown in Figure 2b. Then, the produced fine particles were ground to powder using the grinding machine, as shown in Figure 2c. The powder is finally sieved, as shown in Figure 2d, to produce the used powder as the RG fine aggregate in the plain and fibrous mixtures, where it includes 70% of the particles passed from the 300 µm sieve and retained on the 150 µm with 30% of the finer particles passed from the 150 µm sieve and retained on the 75 µm.

Table 2. Properties of the used PVA fibers.

Fiber Type	Length (mm)	Diameter (µm)	Fu (MPa)	E (GPa)
PVA	6	39	1620	42.8

(**a**) (**b**)

Figure 1. Used materials. (**a**) PVA fibers, (**b**) silica sand.



(**a**) (**b**) (**c**) (**d**)

Figure 2. Production process of the RG fine aggregate. (**a**) Manually crushed large RG; (**b**) Los Angeles crushed medium-size RG; (**c**) fine-ground RG aggregate; (**d**) sieve grading of RG.

2.2. Mechanical Tests

From each mixture, 12 cubes and 12 beam specimens were cast in groups as shown in Figure 3. After demolding, the specimens were stored in water containers until the test age. The curing water was maintained at a temperature of approximately 20 ± 3 °C. The cubes were 100 mm in side length and were used to conduct the compressive strength test, while the beams had a square cross-section with a side length of 100 mm and a length of 400 mm. The beams were tested under four-point bending configuration over a span of 300 mm and shear-spans of 100 mm to evaluate the flexural strength or the modulus of rupture. The tests were conducted at three ages of 7, 28, and 90 days with four specimen replications for each test. Therefore, a total of 192 cube and beam samples were prepared and tested in this study from the 8 mixtures.

Figure 3. Cast cube and beam specimens.

3. Results

As detailed in the previous section, the compressive strength (Fc) and flexural strength or modulus of rupture (Fr) are the mechanical tests considered in this study. Each was tested at three ages of 7, 28, and 90 days for both groups of ECC mixtures, where the use of PVA fiber was the variable between the two groups and the percentage replacement ratio of silica sand by RG filler was the variable investigated within each of the two groups. Figure 4 summarizes the compressive strength results of the eight mixtures at the three ages, while Figure 5 summarizes their flexural strength results.

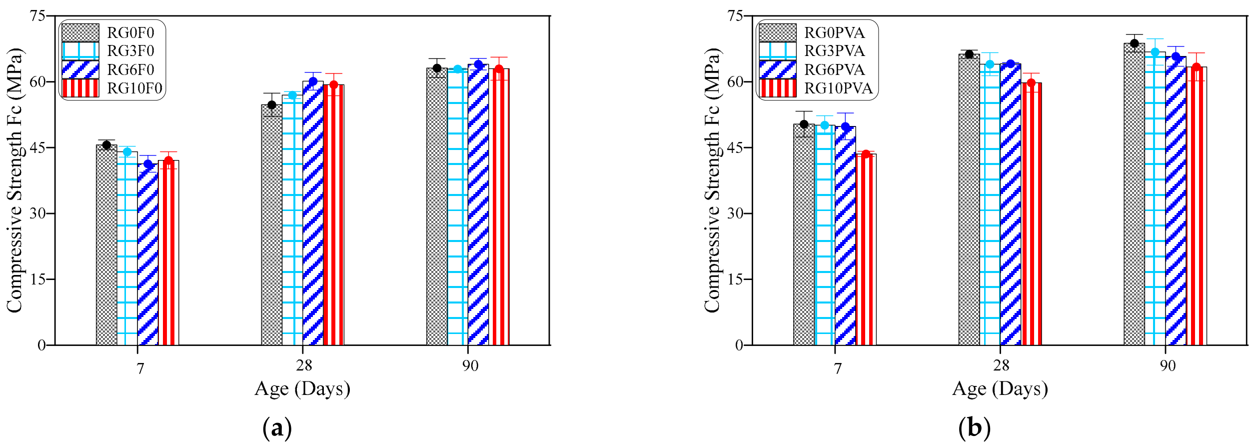


Figure 4. Compressive strength of all mixtures at different ages. (**a**) Plain, (**b**) PVA fiber.

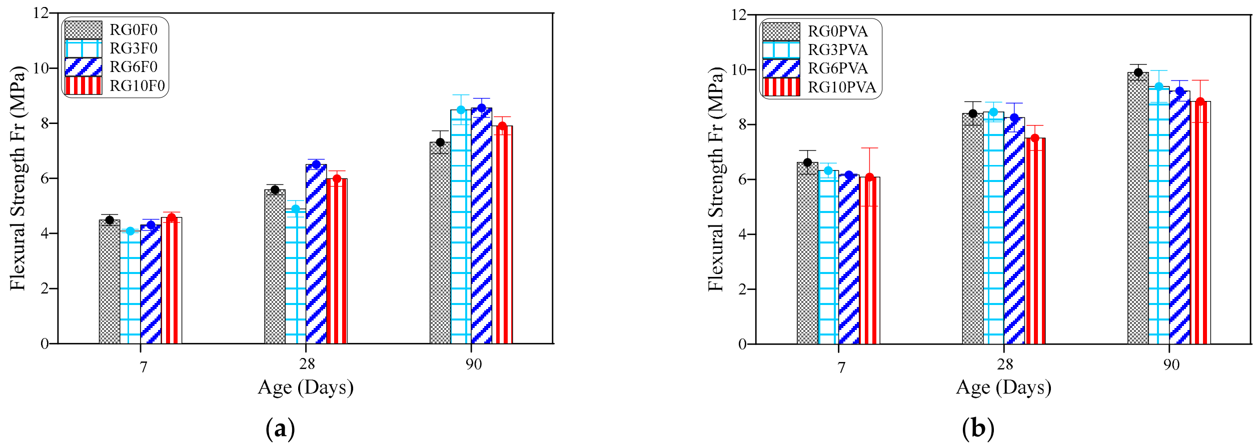


Figure 5. Flexural strength of all mixtures at different ages. (**a**) Plain, (**b**) PVA fiber.

Figure 4a shows the compressive strength results of the four plain mixtures. The figure reveals the development of the compressive strength with age with the highest development obtained from 7 to 28 days. The compressive strength at 7 days of age of the four mixtures ranged from 41.3 to 45.6 MPa, while the results range was from 54.8 to 60.1 MPa at 28 days and 62.9 to 64.0 MPa at 90 days. Considering the average value of the four mixtures at each age, a strength development of 33.6% was gained from 7 to 28 days, while only 9.4% development was gained from 28 to 90 days. Similarly, in Figure 4b, which displays the compressive strength results of the PVA fiber-reinforced mixtures, it is shown that the averages of compressive strength records were from 43.6 to 50.4 MPa, 59.8 to 66.3 MPa, and 63.4 to 68.8 MPa at ages of 7, 28, and 90 days, respectively. Therefore, the strength age developments were 31.1% from 7 to 28 days and 4.2% from 28 to 90 days.

Figure 5 shows that the flexural strength exhibited more apparent strength development after 28 days of age. For the plain mixtures (Figure 5a), Fr records were in the ranges of 4.09 to 4.59 MPa, 4.89 to 6.51 MPa, and 7.31 to 8.56 MPa at ages of 7, 28, and 90 days, respectively. Therefore, the percentage strength development from 7 to 28 days was 31.5%, while that from 28 to 90 days was 40.4%. The PVA-reinforced specimens retained higher Fr records as shown in Figure 5b, where the strength ranges at 7, 28, and 90 days were from 6.09 to 6.62 MPa, 7.51 to 8.46 MPa, and 8.84 to 9.90 MPa, respectively. Considering the averages of the four mixtures, the percentage developments from 7 to 28 and from 28 to 90 days were 29.5 and 14.5%, respectively. Generally, from Figures 4 and 5, it can be noticed that at each age, the compressive strength and flexural strength of the specimens incorporating PVA fibers were higher than their corresponding plain specimens. This result is attributed to the crack bridging activity of fibers that postpone the failure and increase the strength.

4. Discussion

4.1. Plain ECC Mixtures

The influence of silica sand substitution by RG is discussed in this section, where the effect of the different replacement ratios is considered for plain and fibrous specimens and at each age. Figure 6 displays the effect of gradual replacement of silica sand by RG on the compressive strength of the plain specimens. Figure 6a shows that the early age compressive strength of all mixtures incorporating RG was lower than that of the reference specimens RG0F0, where as shown in the blue line, the ratio of the compressive strength of specimens with RG to those without RG, which is defined in this study as the residual strength ratio, is less than 1.0 (the red horizontal line) for all mixtures. On the other hand, this situation was reversed at the mature age of 28 days, where as depicted in Figure 6b, the residual strength ratio exceeds 1.0 for all RG replacement ratios. The results at 90 days also agree with those at 28 days but with less effect of RG on the strength, where the residual strength ratio fluctuates very closely around the neutral red line (ratio = 1.0) as shown in Figure 6c.

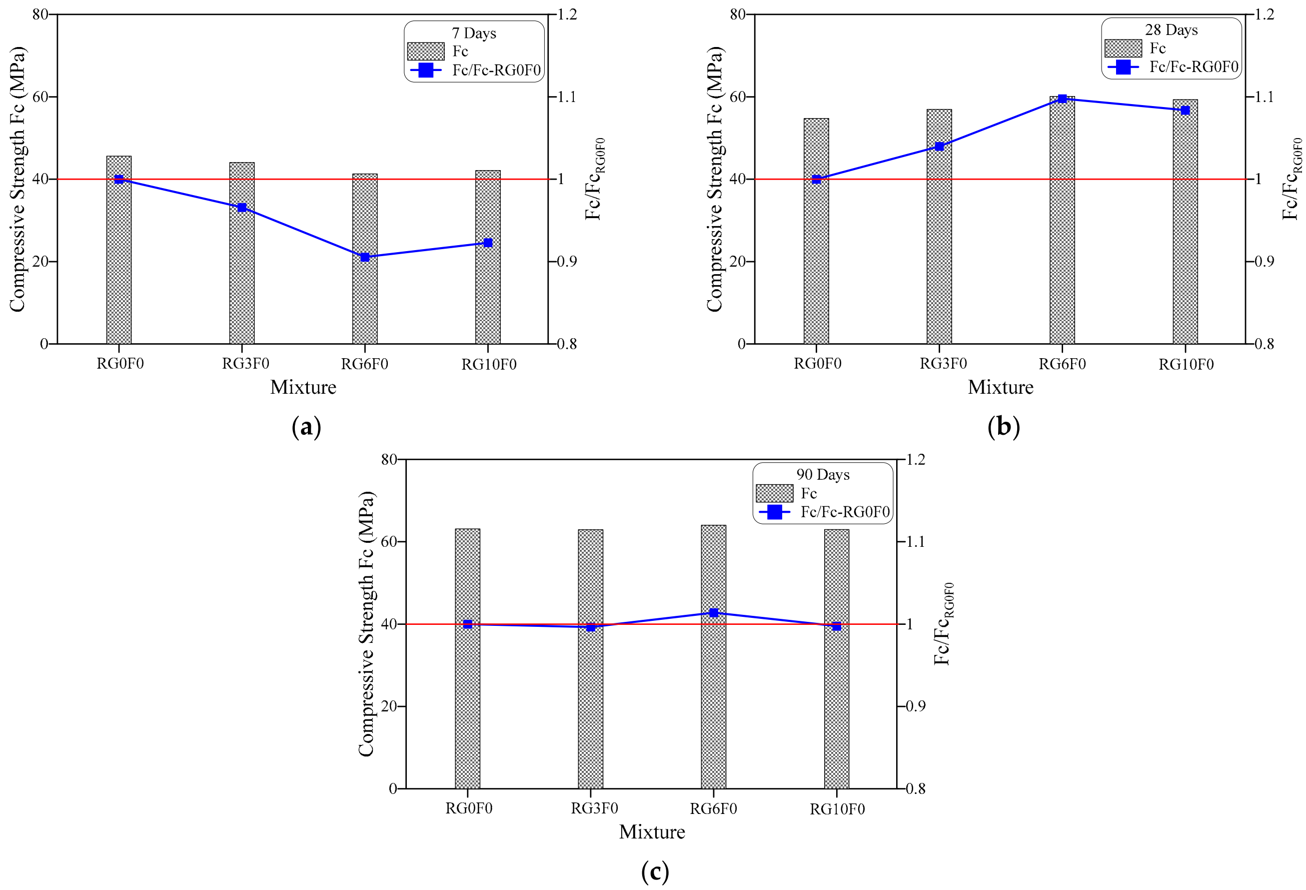


Figure 6. Compressive strength of plain specimens with different RG percentages at ages of (**a**) 7 days, (**b**) 28 days, (**c**) 90 days.

There are two points that should be discussed to understand the results presented in Figure 6. The first point is the strength decline at early age, while the second is the strength gain or at least the semi-neutral effect at mature ages. It was reported by previous studies [32,37,68] that using RG as an aggregate replacement may increase the segregation and bleeding issues owing to the shape and surface conditions of RG particles. The smooth surface of RG and its amorphous configuration in addition to its low water absorptivity may negatively affect the bond (adhesion) with the surrounding cement paste [21]. Moreover, density reduction was reported by previous studies [22,25,37], which might be another source of compressive strength reduction. As a result, a strength decline is expected at early ages for these reasons. Several previous studies support the obtained results of this study, where they reported a strength decrease at early ages with RG increase [31,32,69]. On the other hand, the strength increase in mature specimens with the use of RG can be attributed to the pozzolanic activity of glass powder [61] as fine glass particles exhibit pozzolanic reaction, which reduces the microstructure's pores and increases the strength [7]. It was reported that glass particles with sizes of not more than 100 µm showed proven pozzolanic activity [70,71]. In addition, finer particles better fill the microstructural pores resulting in a denser structure [69], which increases the strength. However, the pozzolanic activity of glass powder is slow at early ages and is more apparent at mature ages [40,68,72], which explains the strength development at 28 and 90 days of specimens with RG and their strength reduction at 7 days of age. The late or extended pozzolanic activity of RG powder is attributed to its higher content of CaO compared to natural sand, which explains the obtained late development of strength [69].

Figure 7 shows the flexural strength results of the plain group specimens. The results showed some kind of agreement with those of compressive strength but did not follow exactly the same trends. For the early age specimens (7 days), the specimens with 30 and 60% RG retained lower Fr than the reference 0% RG specimens, where the residual strength ratios were 0.91 and 0.96 for the two RG percentages, respectively. However, the flexural strength of the 100% RG was very comparable to that of the reference specimens with only 0.1 MPa increase in Fr, which is shown in the blue line (Figure 7a) as only approximately 2% increase in the residual strength ratio. On the other hand, the flexural strength was developed at the mature age of 28 days, but replacing 30% of RG seems to be not enough to develop Fr higher than the reference specimens. The residual strength ratios were 0.88, 1.16, and 1.07 for RG replacement ratios of 30, 60, and 100%, respectively as shown in Figure 7b. On the other hand, the mature specimens at 90 days exhibited a full strength increase for all RG replacement percentages as for the compressive strength, whereas as depicted in Figure 7c, the residual strength ratios were 1.08 and 1.17 for the specimens with RG filler. This indicates that a similar trend of results to that of Fc was also obtained for Fr but with less effect of the RG late pozzolanic activity on Fr. This might be attributed to the different applied stresses on the material and the different material behaviors under different stresses, where concentric compressive stresses are applied in the compressive strength test, while flexural tensile stresses are the cracking and failure causing stresses under bending.

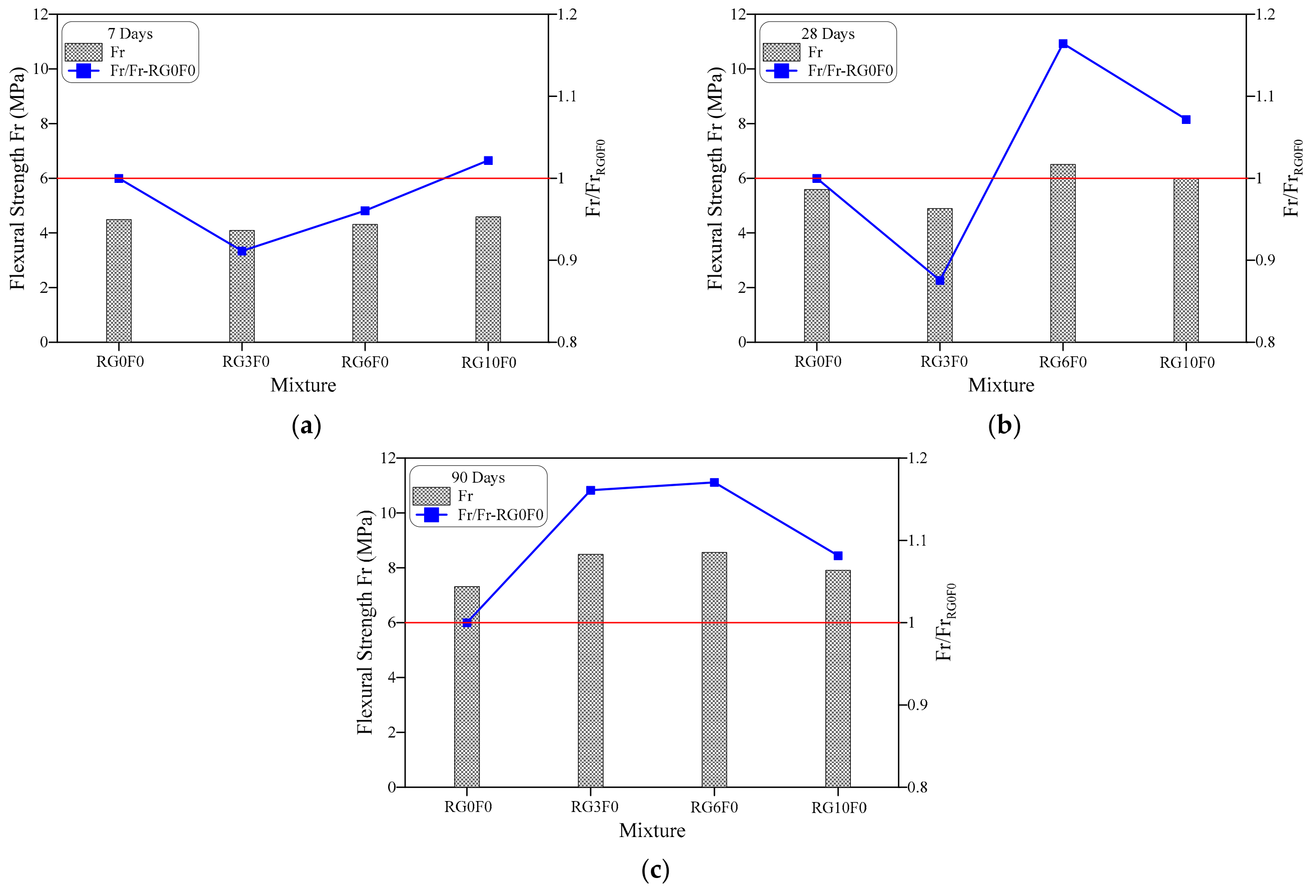


Figure 7. Flexural strength of plain specimens with different RG percentages at ages of (**a**) 7 days, (**b**) 28 days, (**c**) 90 days.

4.2. Low Cost PVA-ECC Mixtures

Figures 8 and 9 show the compressive strength results and flexural strength results, respectively, of the four PVA-reinforced mixtures. It is clear in both figures that the strength has the same decrease trend at all ages; the strength was lower for the specimens incorporating RG compared to the reference specimens with 0% RG. Figure 8a shows that at 7 days, incorporating 30, 60, and 100% of RG rather than silica sand reduced the compressive continuously, which is also approximately valid for mature specimens at age of 28 days. The blue line in Figure 8b shows this strength decline trend, where the residual strengths were approximately 0.97, 0.97, and 0.90 for specimens incorporating 30, 60, and 100% RG, respectively. Moreover, Figure 8c shows that the mature specimens at 90 days of age exhibited a continuous compressive strength decrease with the increase in RG replacement ratio. The recorded compressive strengths at this age were 68.7, 66.8, 65.8, and 63.4 MPa for RG replacement ratios of 0, 30, 60, and 100%, respectively. Therefore, the residual strength ratios at 90 days were approximately 0.97, 0.96, and 0.92 for the 30, 60, and 100% RG replacement ratios, respectively.

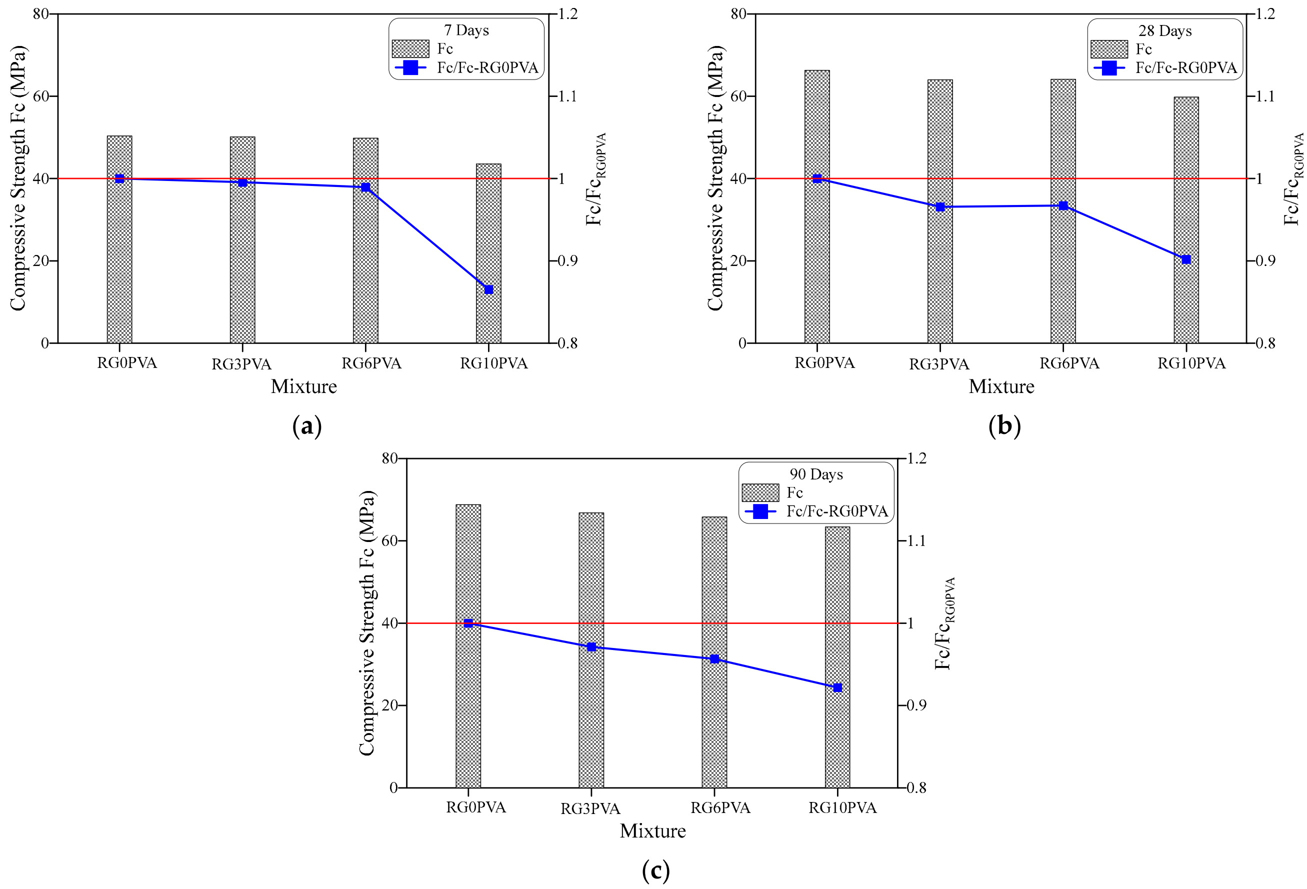


Figure 8. Compressive strength of PVA-fibrous specimens with different RG percentages at ages of (**a**) 7 days, (**b**) 28 days, (**c**) 90 days.

Figure 9 confirms that flexural strength exhibited a similar decrease trend for RG specimens to that of compressive strength. The flexural strength decreased continuously at 7 days of age from 6.62 MPa for specimens without RG to 6.33, 6.17, and 6.09 MPa for beam specimens with 30, 60, and 100% RG, respectively, as shown in Figure 9a, which resulted in residual strength ratios of approximately 0.96, 0.93, and 0.92, respectively. The flexural strength specimens at 28 days (Figure 9b) showed a similar trend but with a very slight strength increase for RG replacement ratio of 30% of only 0.05 MPa, which was followed by a continuous strength reduction recording residual strength ratios of approximately 0.98 and 0.89 for RG replacement ratios of 60 and 100%, respectively. As for the compressive strength, the continuous flexural strength decline with RG replacement ratio was more apparent at 90 days as shown in Figure 9c. As it is clear in the blue line, the residual strength ratio declined from 1.0 to 0.95, 0.93, and 0.89 with the increase in RG replacement ratio from 0 to 30, 60, and 100%, respectively.

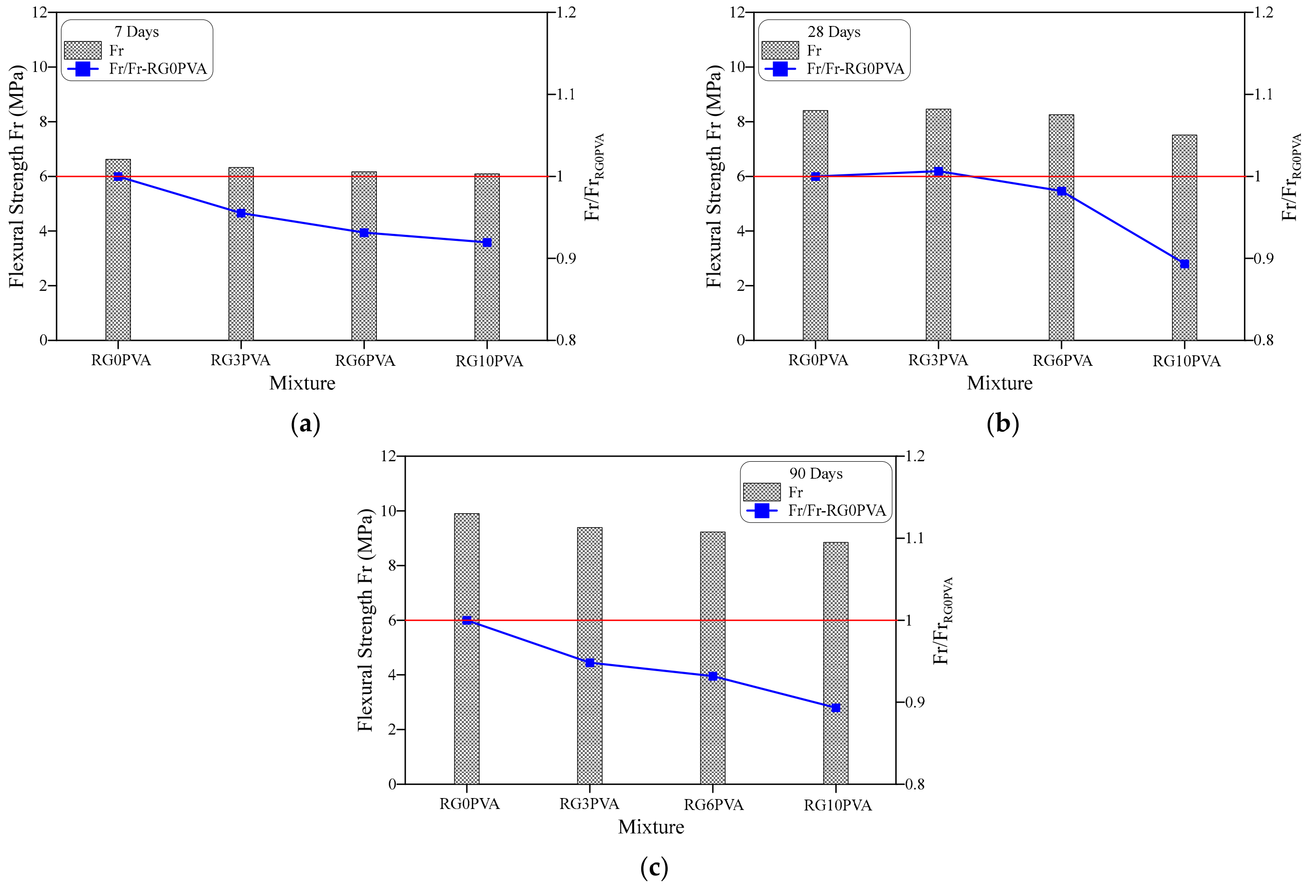


Figure 9. Flexural strength of PVA-fibrous specimens with different RG percentages at ages of (**a**) 7 days, (**b**) 28 days, (**c**) 90 days.

To analyze the above results, the sole effects of PVA fibers and RG should be recognized. Comparing the results of each PVA-reinforced mixture with its corresponding plain mixture (Figures 4 and 5), it is clear that adding PVA fibers increased the compressive and flexural strengths. Figure 10 shows the strength ratios of PVA-reinforced mixtures to their corresponding (same RG content) plain mixtures. Figure 10a reveals explicitly that the use of PVA fibers increased the compressive strength, where all strength ratios are higher than 1.0. This result agrees with the results obtained in previous studies [73,74] using the same mixtures with the same type and properties of the used untreated PVA fibers, where using 2% of this type of fiber increased the compressive strength by approximately 1.5%. On the other hand, adding fibers was very effective on the flexural strength, where as shown in Figure 10b, strength increase percentages of up to 73% were recorded when PVA was incorporated. This effect is attributed to the capability of fibers to postpone cracks widening by carrying the tensile stresses across these cracks, which delays the failure and increases the strength capacity. Using the same type of fiber and the same mixture, it was found in a previous study [74] that the flexural strength was approximately duplicated. As a result, it can be said that the fiber itself increased both compressive and flexural strength regardless of the RG content in the mixture.

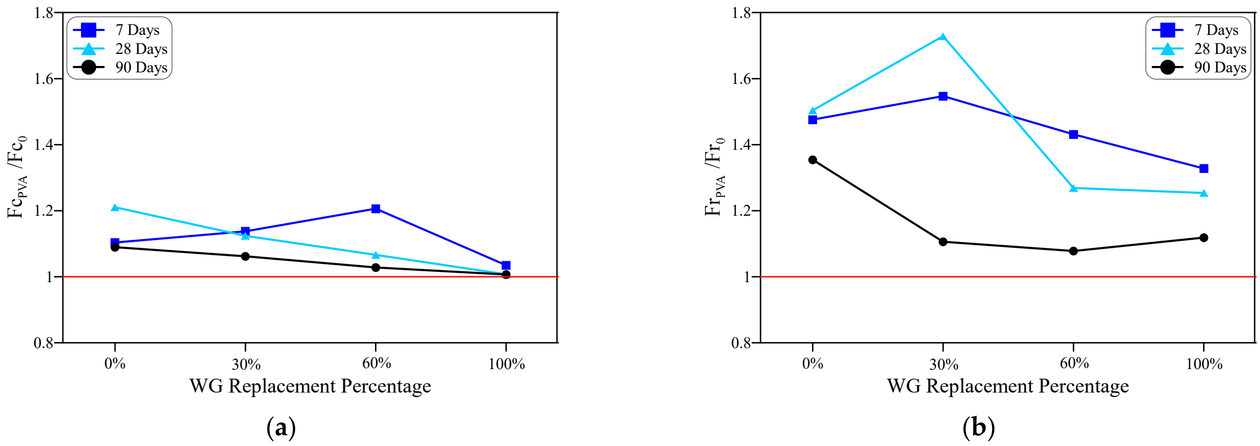
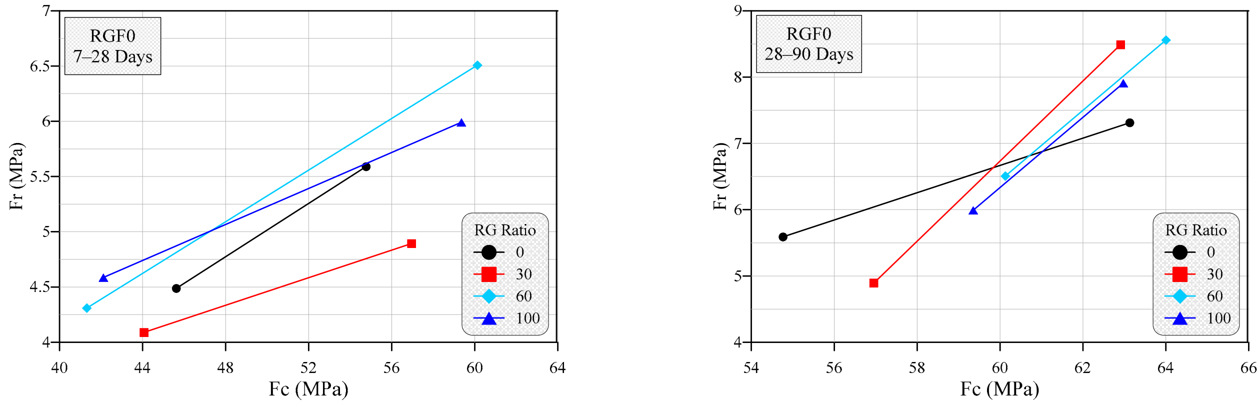


Figure 10. Strength ratio of PVA-fibrous specimens to the corresponding plain specimens. (**a**) Fc, (**b**) Fr.

Recalling the above discussion regarding the positive effect of PVA fibers on the strength and the discussion of Section 4.1 that revealed a positive effect for RG at mature ages, it can be concluded that the combined influence of the used PVA fibers and RG is the only factor that decreased the strength of the PVA fiber-reinforced specimens incorporating RG, as shown in Figure 9. To discuss this decrease, two significant points should be highlighted. The first is that the non-surface-treated low cost PVA fiber is known for its unfavorable high chemical bond with the surrounding cementitious matrix, which is attributed to its surface condition, where it is not oiled as for the typical high cost PVA fibers [75]. Therefore, the dispersion of this type of fiber is not as uniform as that of the typical costly PVA fibers, which may lead to the possible agglomeration of these fibers in the mixture [75]. The second point is the amorphous texture of the used RG particles [7]. Considering the very short length of the used fibers (6 mm), the reason for strength decline might be attributed to the incompatible combination of the micro-RG and micro-PVA fibers, where the sharp ends of RG particles and their amorphous shape might increase the possibility of fiber agglomeration and even fiber rupture during the mixing, which would weaken the microstructure and lead to the strength decline shown in Figures 8 and 9.

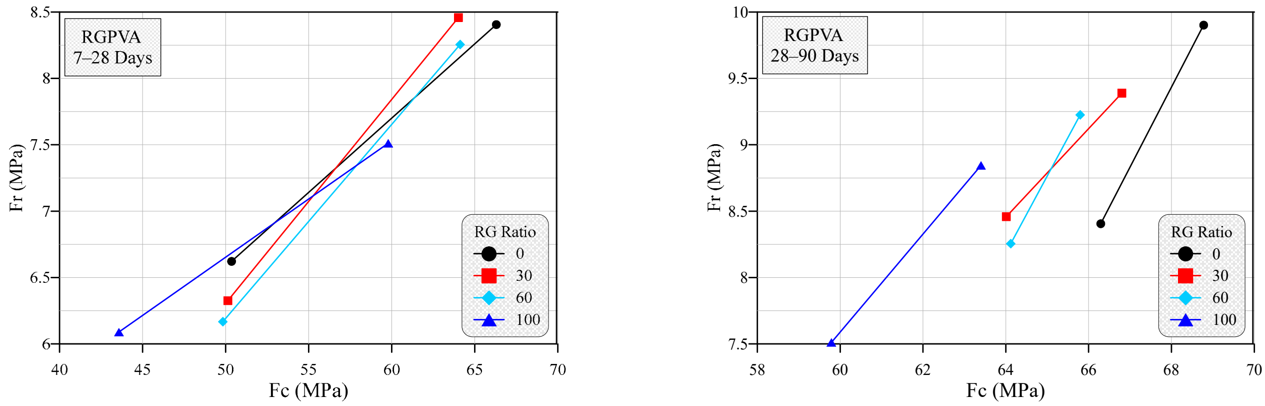
4.3. Compressive–Flexural Strength Relationship

Figures 11 and 12 show the slopes of the compressive–flexural strength relation along the two age development periods from 7 to 28 days and from 28 to 90 days. This relation visualizes the development of flexural strength with the increase in compressive strength for each of the eight mixtures. The figures show that in general, increasing the compressive strength increases the flexural strength of the mixture regardless of RG content or PVA incorporation. Comparing the subfigures of each of the two figures, it can also be noticed that the slopes are higher for specimens with or without fibers at the late maturing period (28 to 90 days) than the early one (7 to 28 days). For instance, the slopes of the plain mixtures range between 0.06 and 0.12 (Figure 11a) from 7 to 28 days, while a higher range of 0.21 to 0.53 is shown in Figure 11b for the period from 28 to 90 days. A similar trend of results is also shown in Figure 12 for the fibrous mixtures. Moreover, of note, the slopes of the fibrous specimens are higher than those of plain ones at both age periods, which reflects the contribution of fiber bridging activity in enhancing the flexural strength. The maximum slopes of the PVA-fibrous specimens at both subsequent periods are 0.15 and 0.6, while those of plain mixtures are 0.12 and 0.53.



(**a**) (**b**)

Figure 11. Compressive–flexural strength development relation with time for plain (RGF0) specimens: (**a**) 7 to 28 days, (**b**) 28 to 90 days.



(**a**) (**b**)

Figure 12. Compressive–flexural strength development relation with time for fibrous (RGPVA) specimens: (**a**) 7 to 28 days, (**b**) 28 to 90 days.

5. Conclusions

The experimental work presented in this study was directed to investigate the possibility of producing more sustainable ECCs with recycled waste glass (RG) powder as filler and low cost surface-untreated PVA fibers. Based on the obtained results and within the limits of the investigated parameters, the following conclusions can be drawn:

1. For plain specimens where PVA fibers were not used, the addition of RG increased the compressive strength at mature ages (28 and 90 days), while this result was not recorded at early age (7 days), which is attributed to the late pozzolanic activity of the finest RG particles (less than 100 µm).
2. The flexural strength of the plain specimens followed approximately similar trends to those of compressive strength at 7 days (decrease) and 28 days (increase), but with slight fluctuations around the reference records. However, the results of flexural strength exhibited an explicit increase for all RG replacement ratios at 90 days, where the strength was 8 to 17% higher than the reference specimens, which fully agrees with the results of the compressive strength at this age.
3. Despite the fact that PVA fibers increased both compressive and flexural strengths, the replacement of silica sand with RG led to a different behavior for specimens incorporating low cost PVA fibers compared to their corresponding plain specimens, where RG replacement decreased both compressive and flexural strengths. The maximum strength decrease was recorded for specimens incorporating 100% RG,

which ranged from 7.8 to 13.5% at the three ages compared to the corresponding specimens with 0% of RG.

4. Increasing the compressive strength increased the flexural strength for all mixtures and at all ages. However, the development ratios of flexural strength compared to compressive strength were higher after 28 days compared to that from 7 to 28 days. This development could be analyzed using the slopes of the compressive–flexural strength relations, which were significantly higher for the 28–90 days of maturing age compared to the earlier one from 7 to 28 days. These slopes were also higher for PVA-reinforced mixtures compared to plain mixtures reflecting the positive effect of fiber bridging role in increasing the flexural strength. The maximum slopes of the fibrous and plain specimens for the 7–28 days period were 0.15 and 0.12, respectively, while they were 0.60 and 0.53 for the 28–90 days period, respectively.
5. As mentioned in the introduction, very few research works were conducted on cementitious composites with partial and full replacement of silica sand by fine recycled glass filler. The utilization of low cost PVA fibers rather than the standard costly surface-treated PVA fibers was investigated in combination with recycled glass filler in this study. It is suggested that the utilization of more sustainable fiber alternatives, such as recycled fibers with recycled glass fine filler in cementitious composites would be a useful and required future study.

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