Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 9481466, 12 pages
https://doi.org/10.1155/2022/9481466

Research Article

Using Recycled Concrete Powder, Waste Glass Powder, and Plastic Powder to Improve the Mechanical Properties of Compacted Concrete: Cement Elimination Approach

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Received 26 March 2022; Accepted 9 July 2022; Published 3 August 2022

Academic Editor: Eleftherios K. Anastasiou

The environment receives millions of tons of garbage, including plastic and glass, and concrete building debris contributes to a number of environmental problems. In order to reduce cement and make use of waste materials like glass and plastic, this research creates compacted concrete samples using waste glass powder, waste plastic powder, micro-silica, fly ash, and recycled powdered concrete. Compressive, nonlinear behavior, and SEM tests on compacted specimens showed that by removing 80% of the cement and substituting 20% recycled concrete powder, 15% micro-silica, 15% fly ash, 15% waste plastic powder, and 15% waste glass powder (at 80°C for 20 minutes), sustainable concrete with compressive and flexural strengths nearly equal to the sample's compressive and flexural strengths was produced. Micro-silica has several shortcomings regarding improving concrete strength and building a suitable combination with recycled concrete powder. In extremely small quantities, glass powder may be used to replace cement, and in greater quantities, it can take the place of aggregate. Finally, it was found that concrete mortar could be made completely sustainable by using recycled materials like glass, plastic, and recycled concrete, as well as micro-silica and fly ash, and that only 20% of the weight of cement could be used without lowering the compressive and flexural strength of the concrete.

1. Introduction

With the shift of population from rural areas to urban ones and the worldwide increase in consumer goods, the world has witnessed an increased rate of construction demolition and plastic waste production. These activities had negative impacts on the environment as well as the economy. The adverse effect on the economy manifests itself in the increased cost of construction materials like sand and limestone due to the overuse of these materials. About 80% of the annual produced gas and oil is used for plastics production [1]. On the other hand, the world's oil production rate is decreasing [2]. The shortage of limestone and sand is another issue that makes the matter critical [3, 4]. Furthermore, inappropriate treatment of waste is another problem that negatively affects the environment. A report issued in 2017 by the U.S. Environmental Protection Agency stated that of the total amount of produced plastic in that country, just 8.3% is recovered and used for recycling or incineration purposes [5]. The remaining produced plastic is either deposited in areas like landfills or illegally dumped. Also, the debris produced as the outcome of the construction and demolition of structures in the US during the year 2018 amounted to 24% of total waste produced in this country [6]. Among the adverse impacts of landfill waste, one could mention the occupation of land resources that are already insufficient and the generation of harmful pollutants entering the air, soil, or groundwater. The cement industry is responsible for up to about 85 of global CO_2 generation in the world, and this rate is expected to increase in the future [7, 8]. These statistics show that the current rates of plastic and concrete use have adverse impacts on the environment regarding sustainability. Reuse, reduction, and recycling are the three *R*'s suggested to countermeasure the issues mentioned above [9]. Among the annually consumed plastics, 42% are used for packaging purposes like preparing or shopping bags [10]. A small value of plastic materials and products is the main reason for the low rates of recycled plastic waste. Besides, recycled plastics are mainly reused for manufacturing products that are lower in quality. Reusing plastic products in the construction industry is a promising solution for disposing of large volumes of plastic waste due to the demand in this sector, as this material does not deteriorate and does not affect performance. It can be used as fibers or aggregates to replace other materials such as sand in concrete [11]. Also, the reuse of these materials compensates for the shortage seen in the amount of raw materials [3, 4]. Various studies have revealed that the use of recycled plastic in concrete increases its tensile strength concerning the ordinary concrete as well as it has a low bulk density [11–14]. But it is noteworthy that the use of high ratios of plastic in concrete reduces its strength due to cement's low hydration in the vicinity of the plastic surface, which is hydrophobic, resulting in reduced adhesion between cement matrix and plastic [11, 14]. Research by Thorneycroft et al. [14] revealed that replacing plastic with 10 wt % sand while increasing both the tensile and compressive strengths of concrete *t* could greatly reduce the rate of recycled plastic waste used by the concrete industry. Thus, larger proportions of plastic waste could be used in concrete production, and the old methods should be modified. The use of recycled materials from construction and demolition practices is under focus in the field of civil engineering as the amount of old transportation, and building structures that should be demolished is increasing [15, 16]. Using recycled aggregates (RA) obtained from the construction industry or demolished buildings to replace raw aggregates in concrete design and production has become a new practice among recycling methods [17–21]. A problem associated with using recycled aggregates (RA) is the high porosity as well as the larger rate of water absorption in the concrete specimens, which are due to hydration of cement paste that is attached to RA, leading to reduced compressive strength and durability in concrete mixes [22]. However, new approaches have been introduced to improve the deficiency of recycled aggregates by reducing the amount of cement paste attached to RA [23, 24]. But high energy consumption by RA has limited their use on a large scale. While removing the attached cement paste by itself further increases the waste production rate. In addition, fine cement mortar grains and solid debris particles are produced during the crushing of demolished concrete. While these very fine particles are gathered, their disposal creates a problem. A proportion of unrecyclable powder resulting from waste concrete crushing remains over the landfill sites although recently promising advances have been made in utilizing powdered waste concrete in the form of cementitious material in concrete mixes [25]. But there is a need for concrete powder grains with a size less than 45 μm to have a proper chemical action which restricts its use in this approach. Sakai et al. [22] introduced a novel approach for concrete waste recycling, which had 100% success without utilizing any new raw material, including cement.

As waste glass has high amounts of amorphous silica in itself, which is necessary for pozzolanic reactivity, many research works have been done to use glass powder or particles in the production of geopolymer concrete. This is done by partially replacing raw materials like cement, aggregates, or SCMs (supplementary cementitious materials) with waste glass powder. This novel technique reduces the cost of concrete production and reduces the amount of CO_2 emission and its adverse effect on the environment during the production of cement or other aggregates used in concrete. This technique reduces the amount of waste glass that otherwise should have been disposed of in nature. Alongside silica, high concentrations of alkali metal oxides present in the composition of the glass (mostly in the form of calcium oxide or sodium oxide) help improve the performance of concrete that contains waste glass because of the alkali-silica reaction (ASR) potential. In general, increasing the fineness of glass particles improves the pozzolanic reactivity and prevents the expansion of ASR [26–28]. The combination of ASR and pozzolanic reactivity considerably improves the durability and properties of the cementitious material using waste glass. The mechanical characteristics of cementitious materials that contain waste glass, such as the flexural, compressive, and splitting tensile strengths, have been comprehensively studied. As there are various types of glasses with different compositions and particle sizes, contradicting results have been reported concerning the advantages or disadvantages associated with using waste glass in cementitious materials. For example, Borhan [29] reported decreased amounts of splitting tensile and compressive strengths for concrete when glass was used as a fine aggregate replacement. Also, Aliet al. [30] reported similar results of reduced flexural, splitting tensile and compressive strengths using waste glass. But there are research works with contradictory results wherein the waste glass has improved the tensile and compressive strengths compared to ordinary concrete [31, 32]. Also, other studies revealed that using optimal percentages of waste glass in cementitious material could result in maximum values for mechanical properties [33]. Furthermore, it was known that curing age greatly affects the strength development of glass powder containing concretes. The mechanical properties of glass-containing concrete may be lower than those of ordinary concrete in a short time. However, the compressive strength increases in the long term due to the pozzolanic reactivity associated with used glass powder [34]. Also, some research works have revealed considerable improvement in durability and other properties of cementitious materials containing glass powder, even in fresh concrete samples [31, 35–37]. In the following sections, the details of some research works are presented. Many review articles have reported that the use of waste glass in cementitious composites has improved the concrete characteristics. Huang et al. [9]; in their review, have discussed the use of solid wastes such as recycled waste glass in pavements made of asphalt. However, they have not included the application of waste glass in cementitious materials and their impact on the durability and mechanical properties of concretes containing waste glass. Shi and Zheng [16] have discussed the use of waste glass in concrete as a replacement for aggregates or cement but have not dealt with the properties associated with the long-term performance of this type of concrete. In their review, Federico and Chidiac [38] discussed the ASR, pozzolanic reactivity, and methods applied for reducing the ASR expansion using waste glass as SSCM in concrete. Rashad [39] has reviewed the durability and other mechanical properties of glass powder containing cementitious materials. However, he has not dealt with the use of waste glass as a replacement for coarse aggregates or cement. In their review, Jani and Hogland [40] mostly concentrated on concrete's thermal and mechanical properties using different ratios of glass replacements. However, other durability factors were excluded from their review. A review by Liu et al. [18] included a performance of waste glass used as precursors and activators and aggregates in alkali-activated materials. Mehta and Ashish [41] provided a summary review of concrete's mechanical properties, workability, and water and chloride permeability using waste glass and silica fume as aggregates. In their review, Khan et al. [42] dealt with shrinkage, absorption, ASR expansion, sulfate and chloride attack, and mechanical characteristics of cementitious materials that contained waste glass. Past research [43–46] has shown that using waste glass powder, micro-silica and fibers can improve the behavior of concrete. Mohajerani et al. [47] extended their review by considering the practical use of waste glass in subbase and base of roads, asphalt concrete, and ultra-weight concrete. In many research works use of waste glass in powder form has improved the tensile strength, but many researchers also have reported they reduced mechanical properties using waste glass in cementitious materials. During the early age curing of waste glass-containing concrete samples, the tensile strength was considerably lower than the ordinary concrete, but with an increase in the curing age of concrete, the adverse effects diminished, and the tensile strength approached that of control concrete sample [34]. Research in the past [48, 49] was shown that using waste materials such as recycled concrete can reduce carbon dioxide production.

Other researchers reported that adding fine glass aggregates at less than 20% proportion does not affect the mechanical properties of concrete, but by increasing the amount of waste glass content, both the flexural and compressive strengths of concrete decreased. Similarly, Malik et al. [50] replaced 40% of fine aggregates with glass powder in concrete samples and found that both the tensile and compressive strengths reduced with increasing the waste glass ratio from zero to 40%.

Research in the past has shown that recycled materials can be used in the concrete today, including waste glass and recycled plastics. This paper aims to replace all or part of the cement with sustainable materials such as micro-silica, fly ash, waste glass powder, waste plastic powder, and most importantly, all recycled concrete powder.

For this purpose, concrete specimens have been made for compressive and flexural tests to test whether the cement can be removed, and substituted sustainable materials can be used instead. Due to the presence of plastic and glass, the samples should be compressed at the beginning of the hydration process and at the same time exposed to heat so that recycled plastics can enter the hydration process faster. The pressure necessary for shaping the specimens in this approach is about 100 Mpa, which is not realized in normal conditions and requires high amounts of energy. Thus, novel methods are needed to reduce the pressure required for forming the samples. Also, recycling large volumes of plastic waste and waste glass in the civil engineering discipline is an issue that should be taken into consideration. This paper introduces a new method to overcome the abovementioned issues by utilizing plastic and glass in the concrete recycling process by compressing them at high temperatures.

The influence of using powdered recycled concrete on compressive strength, flexural strength, and SEM tests and the value of molecular analysis have been explored in the following.

2. Experimental Program

This research aims to use glass and waste plastics in a new form in concrete, eliminating many cement parts. All materials used in this study are green materials that have been mentioned. The flow chart of the experiment is shown in Figure 1.

2.1. Specifications of Used Materials

2.1.1. Cement. In this study, cement type I of the Tehran cement factory is used, and the cement's physical and chemical characteristics are listed in Tables 1 and 2, respectively. In addition, the used cement complies with ASTM C114-85 standard.

2.1.2. Recycled Concrete Powder (RCP). Recycled concrete was crushed using a jaw crusher and then ground and sieved to a size of 200 μm. Recycled concrete used includes ordinary construction concrete.

2.1.3. Fly Ash. According to past research, the best ratio for using fly ash instead of cement is 15% [52], so in this research, 15% of fly ash is replaced with cement. The fly ash (Figure 2) used has been provided from POZZOCRETE 63 (DIRK INDIA).

2.1.4. Superplasticizer. Due to the use of fine materials and to enhance the concrete workability, the POWER PLAST-ES superplasticizer made by Abadgaran Company was incorporated with the polycarboxylate chemical basis according to ASTM C1017 and ASTM C494 standards. This reduces water consumption and enhances the strength and workability of concrete. The amount of used material is 0.3–0.4% by weight of cement. The superplasticizer specifications are shown in Table 3.

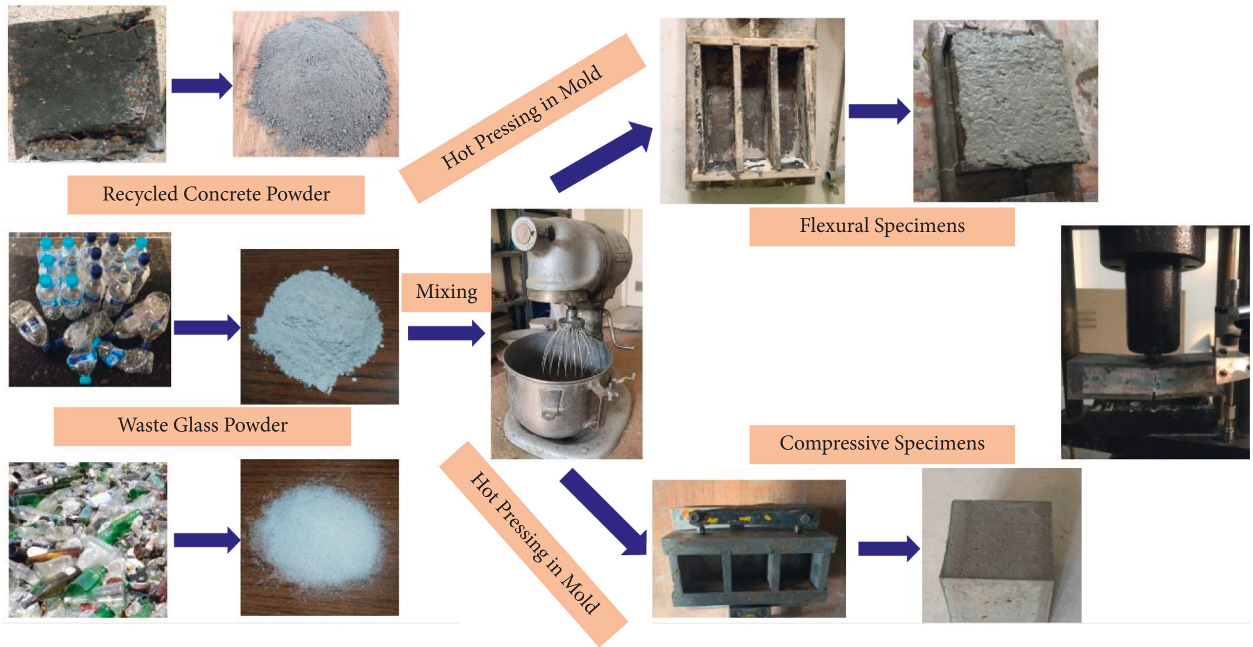


Figure 1: Flow chart of the experiment.

Table 1: Mechanical properties of cement [43].

Properties	Limits	Test method
Fineness	292.33	ASTM C204-16
Initial setting time (min)	94	ASTM C191-13
Final setting time (h)	4.2	ASTM C191-13
3-day age compressive strength (MPa)	13.6	ASTM C109 M-16a
7-day age compressive strength (MPa)	24.12	ASTM C109 M-16a
28-day age compressive strength (MPa)	36.5	ASTM C109M-16a

2.1.5. Waste Plastic Powder (WPP). Plastic bottle waste was used to make plastic powder, which was crushed with the help of industrial mills and sieved to a size of 200 m. According to previous research, it has the optimum impact on compacted concrete. The recycled plastic powder is used at a rate of 15% of the weight of cement. According to past research, it has the best effect on the strength of concrete [53].

2.1.6. Waste Glass Powder (WGP). Waste glass bottles have been used to make glass powder. The waste glass powder (Tables 4 and 5) is divided into 3 sizes. Size 0 to 125 μm is used as cementitious materials in concrete. Size 300 to 500 μm is used as a filler for concrete, and size 500 to 700 μm is used as an aggregate for concrete. Figure 3 shows waste glass powder. waste glass powder in the dimensions of 0 to 125 micrometers has been replaced by cement 15%, and 25% of glass powder has been replaced by aggregate. Previous research (Orouji et al.) had shown that using 25% of waste glass powder as a replacement for fine aggregate has the best effect on enhancing the mechanical properties of concrete.

Table 2: Chemical properties of cement [51].

Compounds	% (by weight)
CaO	64.5
SiO_2	21.68
Al_2O_3	4.6
Fe_2O_3	3.2
SO_3	2.4
K_2O	0.3
Na_2O	0.2
Loss of ignition	1.31
Lime saturation factor	0.4
Insoluble residue	0.84
Main compounds	% (by weight)
C_3S	52.2
C_2S	19.5
C_3A	8.86
C_4AF	10.70

Figure 2: Fly ash was used in this study.

Table 3: Chemical properties of superplasticizer [46].

Properties	
Appearance	Liquid-light brown
Chloride ion	Less than 0.1%
pH	6.5–7.5
Freezing point	2 °C

Table 4: Chemical composition and physical properties of waste glass powder [51].

Chemical composition	%	Physical properties	
Al_2O_3	0.48	Pozzolanic index (%)	77
MgO	3.90	Density (kg/m^3)	1752
CaO	8.82	Fineness modulus	2.82
Fe_2O_3	0.08	Water absorption	0.44
TiO_2	—	Color	White-light gray
SiO_2	69.42		
Na_2O	12.28		
K_2O	0.12		

Table 5: Gradation and rate of used waste glass powder [43].

Size (μm)	% (by weight)
1–125	0.33
300–500	0.33
500–700	0.33

(a) (b) (c)

Figure 3: Waste glass powder: (a) 0–125 μm, (b) 300–500 μm, and (c) 500–700 μm [46].

2.1.7. Micro-Silica. Because most of the cement was removed in this study, micro-silica (Tables 6 and 7) plays an important function in creating adhesion between particles and the compressive and flexural strength of concrete. Excessive usage increases the water absorption of concrete because of the tiny size of micro-silica particles; hence, 15% of micro-silica has substituted cement.

2.1.8. Aggregate. In this study, fine aggregates (grading according to Table 8) are used, and the relevant characteristics are reviewed in continuation. It should be noted that it is necessary to comply with the requirements of ASTM C33 to have high-quality concrete.

Table 6: Chemical properties of micro-silica [42].

By weight %	Compounds
75–98	SiO_2
0.03–5.78	Al_2O_3
0.06–4.54	Fe_2O_3
0.01 ± 0.83	Cao
0.36 ± 0.52	Mgo
1.15 ± 2.02	K_2o
0.17 ± 0.23	Na_2o

2.2. Concrete Mix Design. To make compressed samples, after mixing the materials in the mixer and placing the

Table 7: Physical properties of micro-silica [41].

Physical properties of micro-silica	Limits
Type	Liquid
Color	Milky white
Specific weight (gr/cm^3)	1400

Table 8: Properties of sand [34].

Properties	
Fineness modulus	2.70
Absorption (%)	1.64
Fine aggregate (mm)	0.001–4.75
Density (kg/m^3)	1755
Dust and clay particles (%)	0.35

Table 9: Specimens' specification.

Name	Cement (%)	Fly ash (%)	RCP (%)	Micro-silica (%)	WPP (%)	WGP (%)
C40R0	40	15	0	15	15	15
C30R10	30	15	10	15	15	15
C20R20	20	15	20	15	15	15
C10R30	10	15	30	15	15	15
C0R40	0	15	40	15	15	15
C100R0	100	0	0	0	0	0

Recycled concrete powder: RCP; waste plastic powder: WPP; waste glass powder: WGP.

(a) (b)

Figure 4: Compressive strength: (a) test machine and (b) cubic specimens.

Table 10: Compressive strength.

Specimens name	Compressive strength (MPa)
C40R0	56.41
C30R10	52.81
C20R20	49.36
C10R30	46.53
C0R40	37.18
C100R0	51.34

samples in the mold, they are compressed for 20 minutes at 80°C, and after 24 hours, they are taken out of the molds and kept in water for 28 days. After the concrete specimens are exposed to pressure and heat, the plastics begin to melt and enter the hydration process. Then compressive and flexural strength tests were performed on them. Compressive strength was performed based on ASTM C109, and flexural strength was performed based on ASTM C348 in Table 9, specific specimens are mentioned. For each of the mentioned mixing designs, three compressive and flexural samples have been made, and the presented results are the average of the obtained results. The water to cement ratio (W/C) has remained constant at 35% with a superplasticizer. Compressive strength specimens' sizes are 5×5 cm, and flexural strength specimens' sizes are $4 \times 4 \times 16$ cm.

3. Test Results

The tests performed on the samples are divided into two parts: mechanical tests and tests related to microstructure. In

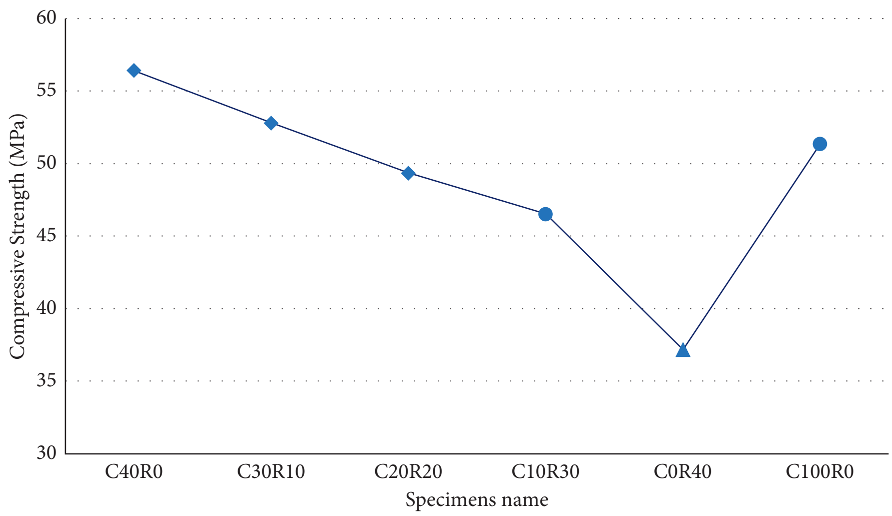
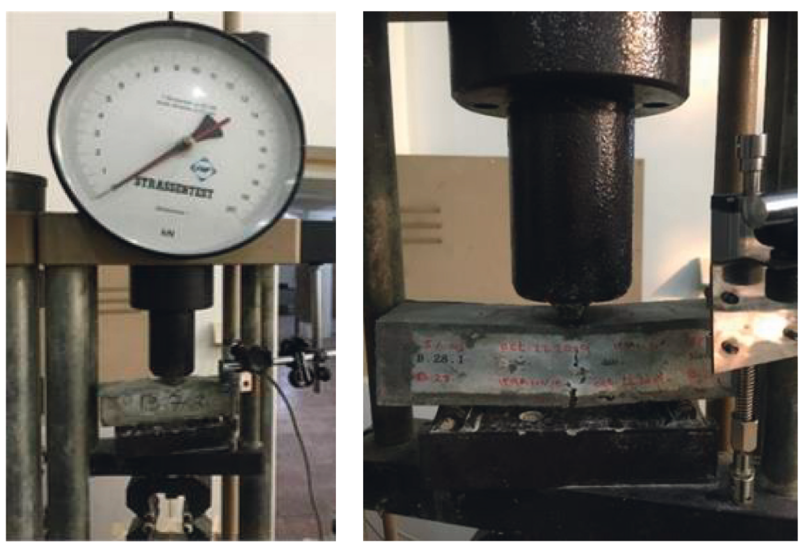


Figure 5: Comparison of compressive strengths.



(a)

(b)

Figure 6: Flexural test: (a) test machine and (b) flexural specimen.

the mechanical tests section, two tests of compressive strength and flexural strength were tested on the samples, and in order to examine the microscopic structure of the samples, the SEM test was performed.

3.1. Compressive Strength Test Results. After 28 days, the cubic specimens were tested according to ASTM C109 (Figure 4), and the compressive strength results of an average of 3 specimens for each mixing design are shown in Table 10.

Table 6 and Figure 5 show that the control sample with ordinary cement had a compressive strength of 51.34 MPa. The sample contains 40% cement, 15% fly ash, 15% waste glass powder, and 15% recycled plastic, compressive strength of 56.41 MPa, which is higher than other samples.

Table 11: Load-displacement diagram.

Specimen name	Flexural strength (KN)
C40R0	8.74
C30R10	7.65
C20R20	6.94
C10R30	5.23
C0R40	4.27
C100R0	6.21

The higher the use of powdered recycled concrete, the lower the amount of cement and the lower the compressive strength of concrete. However, using 20% recycled concrete and 20% cement, the compressive strength of concrete is

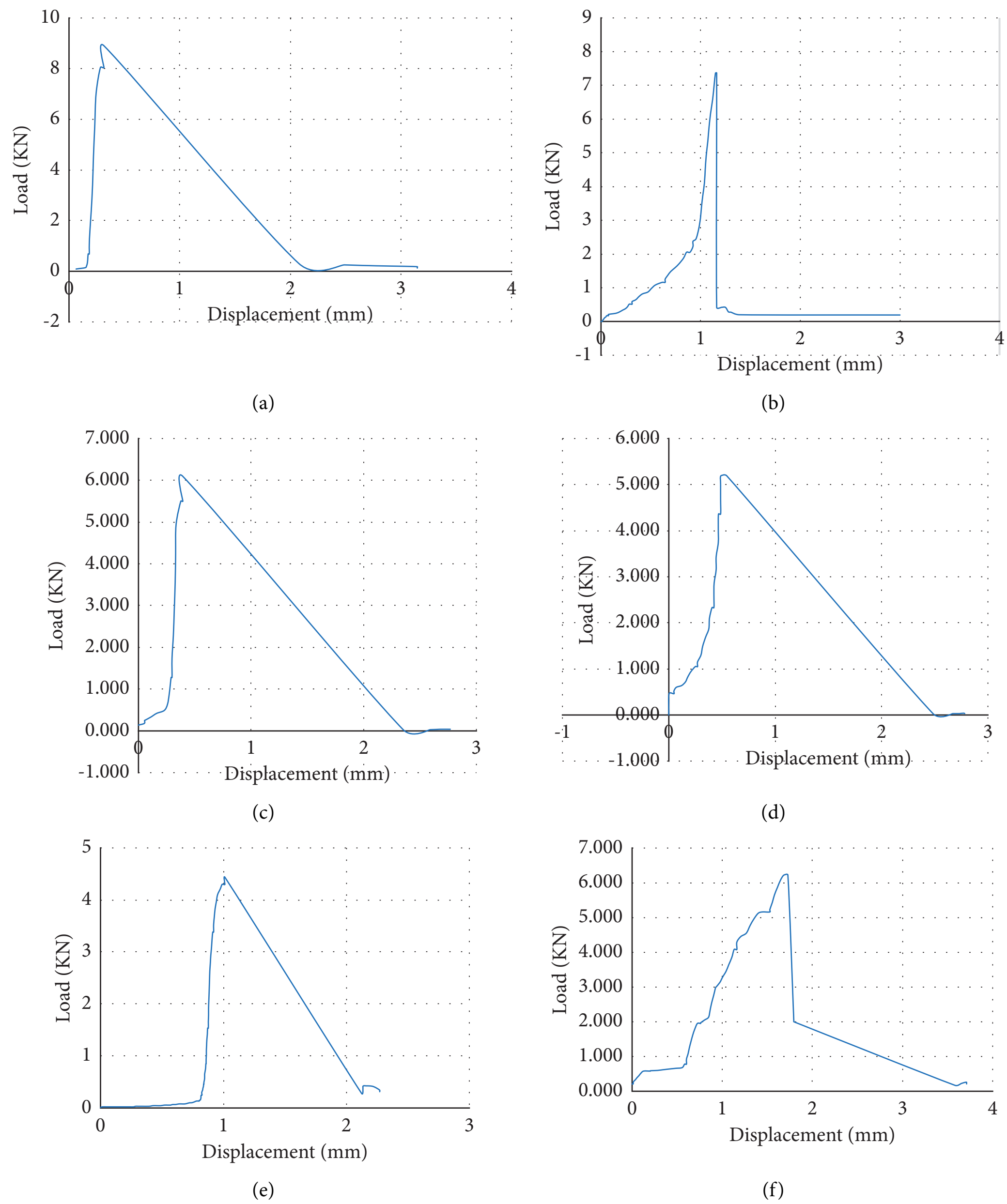


Figure 7: Load-displacement diagram. (a) C40R0, (b) C30R10, (c) C20R20, (d) C10R30, (e) C0R40, and (f) C100R0.

49.36 MPa, which is approximately equal to the compressive strength of the control sample.

3.2. Flexural Strength Test Results. Samples with dimensions of $16 \times 4 \times 4$ cm were tested according to the standard (Figure 6), which are shown in Table 11 and Figure 7.

The results of flexural strength tests are the same as compressive strength. The best result is for the first sample, and by using 20% of cement and replacing it with green materials, the flexural strength of concrete is almost equal to the strength of the control sample. The flexural strength of specimen C40R0 is 8.74. The lower the amount of cement, the lower the flexural strength of the samples. So by completely omitting the cement and replacing it with Waste Concrete Powder, the flexural strength will be 4.27 KN, which is the lowest among the other samples.

3.3. SEM Test and IDFix Report. Because of the relevance of morphological analysis and the research on micro-silica behavior, as well as waste glass powder, waste plastic powder, and fly ash, SEM analysis has been applied. The SEM analysis is shown in Figures 8 and 9.

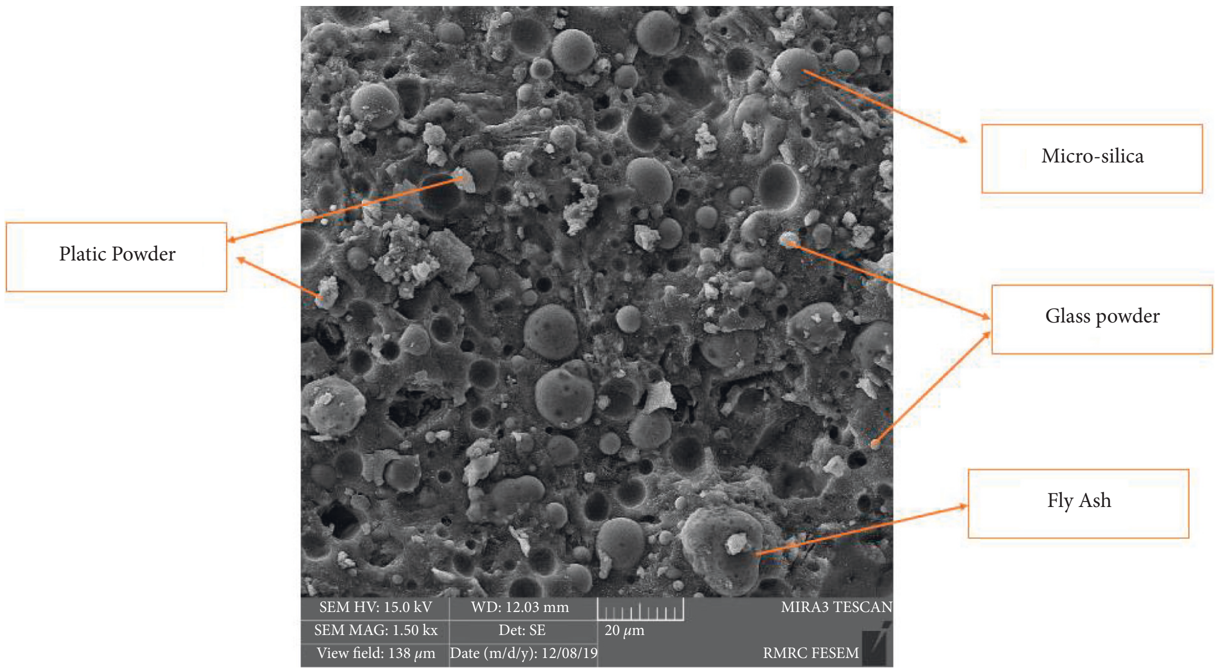


Figure 8: Effect of sustainable materials on concrete (C30R10) [46].

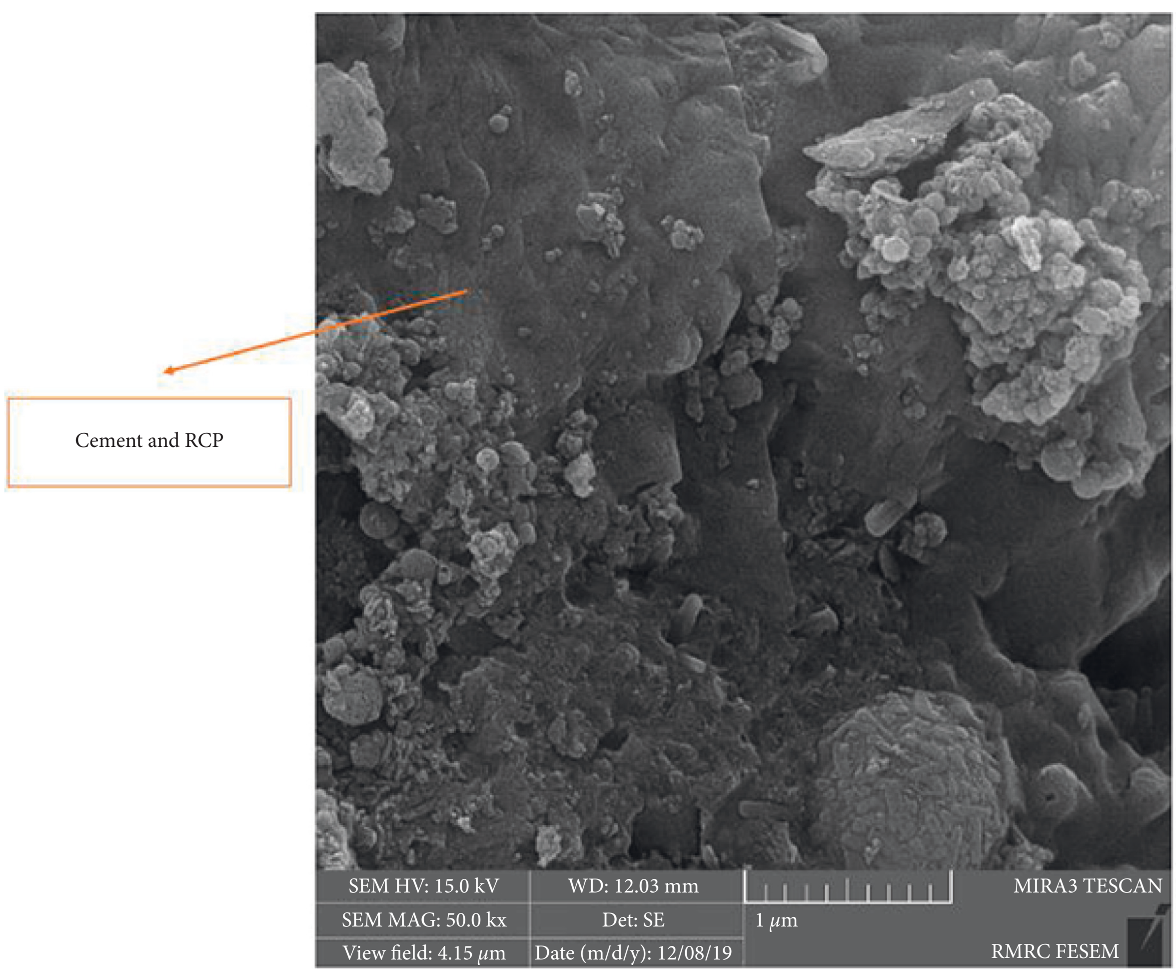


Figure 9: Cement hydration gel formation (C30R10).

As shown in Figure 9, powdered recycled concrete particles along with cement have participated well in the hydration process.

4. Conclusion

The following findings were obtained after producing experimental samples and performing compressive strength tests, flexural strength tests, and SEM testing on the samples. Sustainable concrete may be made by combining waste glass powder and waste plastic powder with powdered recycled concrete, which has excellent compressive and flexural strength [1, 4, 23, 42, 54–58]:

(1) When the concrete is compressed at 80°C for 20 minutes, the plastic and glass particles immediately enter the hydration gel and participate in the hydration process. Complete cement elimination reduces the compressive and flexural strength of concrete significantly. The sample had the greatest results when it contained 40% cement and 15% fly ash, 15% micro-silica, 15% waste glass powder, and 15% waste plastic powder.

(2) By eliminating 80% of the cement and replacing it with 20% recycled concrete powder, sustainable concrete with compressive and flexural strengths is almost equivalent to the compressive and flexural strengths of the sample prepared with 100% cement may be produced. Micro-silica has numerous flaws in terms of enhancing concrete strength and forming an appropriate combination with recycled concrete powder.

(3) In very tiny dimensions, the glass powder is a suitable substitute for cement, and in larger dimensions, it is a good substitute for aggregate. Finally, it was discovered that by using recycled materials such as glass bottles, plastic bottles, and recycled concrete, as well as micro-silica and fly ash, the concrete mortar could be made completely sustainable, and only 20% of the weight of cement can be used without reducing the compressive and flexural strength of the concrete.

Data Availability

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors appreciate the Structure and Construction Materials Laboratory of Tarbiat Modares School of Engineering, Tarbiat Modares University (TMU), and Shahid Beheshti University (SBU) for their assistance in the experimental works.

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