Research Article

Erfan Najaf, Maedeh Orouji, and Seyed Mehdi Zahrai*

Improving nonlinear behavior and tensile and compressive strengths of sustainable lightweight concrete using waste glass powder, nanosilica, and recycled polypropylene fiber

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Abstract: Concrete is one of the most extensively utilized building materials that can be produced, and has the potential to release a significant quantity of CO₂ into the environment. In this research, through studying lightweight (LW) concrete, attempts are made to produce environmentally friendly LW concrete with high strength using nanosilica rather than part of the cement and waste glass powder instead of aggregates. Recycled polypropylene fibers are used to increase the concrete's compressive strength and nonlinear behavior. The use of glass powder was 20, 25, and 30% of the weight of aggregates, the consumption of nanosilica was 1, 2, and 3% of the weight of cement, and the consumption of recycled fibers (FORTA Ferro-Green) was 0.5, 1, and 1.5% of the weight of cement. Leca is also utilized as a LW aggregate. According to 7- and 28-day experimentation results and field emission scanning electron microscope analysis, the best sample had 1.5% fiber, 3% nanosilica, and 25% waste glass powder, and had a compressive and tensile strengths of roughly 1.7 and 1.6 times, respectively, those of the control specimen after 28 days. Also, using 3% nanosilica instead of cement can reduce greenhouse gas emissions by about 3%.

Keywords: lightweight concrete, nanosilica, waste glass powder, recycled polypropylene fiber, FESEM analysis

1 Introduction

The amount of CO₂ produced during manufacturing of the ordinary Portland cement (OPC) is 7% of total wastes generated in the atmosphere. This amount of CO₂, which also affects produced concrete quality, could be reduced by manufacturing green concrete. The other solution is the application of supplementary materials of cementitious type [1].

Among the cementitious products, one could refer to nanomaterials that possess a very small size, often smaller than 100 nm [2], and due to this feature, they exhibit different mechanical and physical characteristics that make them distinct from other materials. Because of these characteristics, these materials have been under the focus of attention by many researchers and have found applications in various industries in recent decades [3,4]. Also, nanomaterials exhibit increased compressive strength and enhanced permeability when used in cement due to their very large surface area. The increase in compressive strength has been studied by a researcher [3,5], where it has been shown that the addition of nanoparticles as a partial replacement for cement decreases the amount of corrosion; therefore, it has been found that using nanoparticles in ordinary concrete has many advantages. Many researchers have realized that nanoparticles in the concrete make it more compact with a higher homogeneity [6]. Examples of nanosilica in the form of cementitious material are silica [7,8], nanoclay [5,9–12], carbon nanotubes [13,14], nano titania [15–17], nano alumina, carbon nanofiber [18–21], nano zinc [22], nanographene oxide [23], nano metakaolin [24], nano-ZrO₂C, modified montmorillonite clay nanoparticles [25], and nano iron...
This study reviews the research on the effects of nanosilica material on the splitting tensile strength, compressive strength, and flexural strength of lightweight (LW) concrete [28].

Researchers [29] studied the impact of nanosilica on the compressive strength of LW concrete in cellular form. For this purpose, a number of cellular LW concrete specimens that contained nanosilica at 5 wt% of cement were tested. To make a comparison, a number of specimens were also prepared that lacked nanosilica material. The specimens were tested at 3, 7, and 28-days of age. The results of their study revealed that even a slight amount of nanosilica improved the compressive strength in comparison to specimens that lacked this material (Figure 1). Also, it was known that adding nanosilica increases the compressive strength even at early ages, which is due to the pozzolanic activity. Researchers prepared various concrete mixes, including those that lacked any amount of nanosilica (as control specimens) and specimens containing just cement and specimens that contained (1 and 2%) nanosilica and specimens that contained cement and slag at 60% (as an alternative to cement) in addition to the same percentages of nanosilica used in the specimens [31]. Then, they conducted compressive strength tests on the abovementioned LW concrete specimens. Their research results revealed that the compressive strength of both specimens was enhanced by an increase in the percentage of used nanosilica. Furthermore, it was observed that this effect is more obvious in the early ages than later ones. Figure 2 shows the compressive strength test results for various percentages of nanosilica used in the specimens.

In another study, Atmaca et al. examined the impact of adding nanosilica on the mechanical characteristics of high-strength LW concrete [32]. The specimens were prepared in two groups; the first comprised of 5 specimens with different replacement percentages of 0, 10, 20, 30, and 40% of LW aggregates instead of normal aggregates. The second group of specimens comprised the abovementioned materials and percentages but with added nanosilica at 3% to all the specimens. The results of compressive strength tests performed on the specimens showed that the specimens containing nanosilica (at 3%) exhibited a higher compressive strength than those which lacked nanosilica (with the same replaced nanosilica percentages instead of LW material) at different ages (3, 7, 28, and 90 days). Furthermore, the splitting tensile strength was also investigated for the 2 abovementioned groups at 28- and 90-days of age. As observed in Figure 3, it was found that the presence of nanosilica in the LW concrete, regardless of the used percentage of LA aggregates, had caused an increase in the tensile strength.

In another research, researchers used two dosages of nanosilica to achieve high-performance LW concrete [33]. The majority of research works have used dosages in the range of 3–10% of nanosilica in the concrete to examine the behavior of LW concrete with this type of nanomaterial. Due to the high cost of this material, the nanosilica percentages applied in the mixes were 0, 0.05, 0.10, 0.20, and 1 wt% of cement in the compressive and flexural strengths tests. The results revealed a nonlinear

![compressive strength comparison](image_url)
relation between dosages of used nanosilica and the tensile and compressive strengths, and even a small percentage of nanosilica could improve the compressive strength and flexural strength. Furthermore, it was found that concrete strength is enhanced by up to 0.10 wt% of cement (the critical point), and further increase in nanosilica results in reduced concrete strength properties.

In another study, it was found that adding nanosilica at different dosages enhanced the compressive strength of LW concrete [34]. The authors applied 4 nanosilica percentages of 0, 1, 2, and 3% to examine its effect on the shrinkage, compressive strength, and sensitivity to the formation of initial cracks in the LW concrete specimens prepared with two aggregate types. They found that the compressive strength increases with the age of specimens, and this increase in strength has a higher rate at an early age, but then it decreases with time. The other finding was that the maximum compressive strength was obtained at 3% use of nanosilica, which was true for all the specimen ages, i.e., 3, 7, and 28 days. Concerning the shrinkage test, it was observed that adding nanosilica at all the studied percentages did not have a noticeable effect on the long-term shrinkage strain of the LW concrete specimens, but increasing the nanosilica dosages in LW concrete specimens caused an increase in the shrinkage strain percentage. It has been illustrated by Kamasamudram et al. that

Figure 2: Compressive strength of LW concrete; (a): cement + nanosilica and (b) cement + slag + nanosilica [31].

Figure 3: Splitting tensile strength of LW concrete [32].
nanosilica has a positive effect on cement paste rheology, microscopic phase formation, hydration, and compressive strength [35].

Furthermore, it was observed that using nanosilica caused a reduction in the area where early cracks were formed in LW concrete. Other researchers also applied different ratios of nanosilica in LW concrete to study the characteristics of LW concrete specimens made with LW aggregates [36]. The concrete used for testing by the researchers mentioned above had a density in the range of 1,400–1,500 kg/m³. Assessing the role of nanosilica in the behavior of specimens made of LW concrete was based on the results obtained from conducting tests of tensile and compressive strengths having nanosilica ratios of 0, 0.75, 1.5, and 2.5%. The obtained results showed that adding nanosilica clearly increases both the tensile and compressive strengths, and the obtained results were much higher than those obtained from specimens that lacked nanosilica. The authors reported that the mixtures containing 0.75 and 2% nanosilica exhibited higher strength than the specimens containing 1.5% nanosilica, but the maximum tensile strength corresponded to 2% use of nanosilica in the specimens. Researchers, in another research, examined the effect of adding nanosilica on the compressive and flexural strengths of mixtures having densities ranging from 900 to 1,000 kg/m³. They used nanosilica at 0, 1, 2, and 4 wt% of cement in the mixtures [37]. Their research also revealed an obvious increase in the compressive strength of concrete specimens by adding nanosilica. The same results were obtained for the flexural strength, especially at 2 and 4 wt% of cement ratios. In another research, Suleiman et al. investigated the compressive strength of LW concrete wherein burnt bricks were used as coarse aggregates, and nanosilica was added to the specimens at 0, 1, 2, and 3%. They concluded that increasing the ratio of used nanosilica increases the compressive strength, and the maximum strength corresponds to 3% use of nanosilica [30]. Orouji et al. found that adding 1.5% fiber in concrete improves flexural strength significantly [38]. In another research, Mortezagholi et al. deduced that using microsilica gel can improve compressive and flexural strengths of concrete [39]. McSwain et al. found that using fibers in concrete can make ultra-high-performance concrete [40]. Also, Landis et al. proved that fibers in concrete could improve the energy dissipation mechanism [41].

According to previous research, it was found that using nanosilica can increase the compressive strength of LW concrete. In this study, waste glass powder and recycled polypropylene (PP) fibers are used to make LW and environmentally friendly concrete from nanosilica. Percentage of used nanosilica is 1, 2, and 3% instead of cement weight, percentage of used waste glass powder is 20, 25, and 30% instead of fine aggregates, and percentage of recycled PP fibers is 0.5, 1, and 1.5% by weight of cement. After making compressive and tensile specimens and performing slump tests, the specimens are tested according to the standard after 7 days and 28 days, and their results are evaluated.

2 Experimental program

2.1 Specifications of used materials

2.1.1 Water

The water quality and conditions in fiber-reinforced concrete are similar to those in regular concrete. Water should be devoid of dangerous chemicals such as iron oxides, acids, alkalis, salts, organic debris, chloride ions, and other contaminants. Impurities in water may disrupt cement setting, diminish concrete strength and durability, create discoloration, stain the concrete surface, and even corrode the reinforcing. In this investigation, drinking water was utilized. Table 1 shows the chemical properties of water.

| Water resource | TDS   | Sulfate | CaCO³ | pH  |
|----------------|-------|---------|-------|-----|
| Drinking water | 339   | 56      | 135   | 7.3 |

2.1.2 Superplasticizer

Due to the usage of fibers and the difficulties in combining fibers with concrete, and to improve the workability of the concrete, Abadgaran Company’s POWER PLAST-ES superplasticizer with polycarboxylate chemical base was included following ASTM C1017 and ASTM C494 standards. This minimizes water usage while increasing concrete strength and workability. The material utilized is 0.3–0.6% of the cement’s weight. Table 2 shows the superplasticizer specs.

2.1.3 Nanosilica

According to the previous studies, by the addition of nanosilica, the concrete strength increases, but on the
other hand, too much nanosilica, due to the fineness of grains, increases water absorption amount concerning cement. This consequently increases the amount of concrete water and reduces the strength. Therefore, to investigate the role of nanosilica on concrete strength, 3 nanosilica dosages of 1, 2, and 3% were used for cement replacements. In Tables 3 and 4, chemical and physical properties of nanosilica are shown, respectively.

| Table 2: Chemical properties of superplasticizer |
|-----------------------------------------------|
| **Properties**                               | **Appearance** | **Liquid-light brown** |
| Chloride ion                                 | Less than 0.1% |
| pH                                          | 6.5–7.5        |
| Freezing point                               | 2°C            |

| Table 3: Chemical properties of nanosilica |
|--------------------------------------------|
| **By weight (%)**                          | **Compounds** |
| 75–98                                      | SiO₂          |
| 0.03–5.78                                  | Al₂O₃         |
| 0.06–4.54                                  | Fe₂O₃         |
| 0.01 ± 0.83                                | CaO           |
| 0.36 ± 0.52                                | MgO           |
| 1.15 ± 2.02                                | K₂O           |
| 0.17 ± 0.23                                | Na₂O          |

| Table 4: Physical properties of nanosilica |
|--------------------------------------------|
| **Physical properties of nanosilica**      | **Limits** |
| Type                                       | Liquid      |
| Color                                      | Milky white |
| Specific weight (g/cm³)                    | 1,400       |

| Table 5: Gradation and dosage of waste glass powder |
|-----------------------------------------------------|
| **Size (μm)**                                       | **% (by weight)** |
| 1–125                                                | 0.33            |
| 300–500                                              | 0.33            |
| 500–700                                              | 0.33            |

2.1.4 Aggregate

2.1.4.1 Sand, gravel, and Leca

In this research, the used rock materials included the river bed sand and LW Leca produced by Leca Co. of Saveh City. The sand grading was performed according to ASTM C33 standard, and LW Leca grading was according to ASTM C330.

Leca, due to its unique characteristics such as low weight, low electrical conductivity, appropriate sound insulation, resistance against fire, durability, and chemical stability, is one of the most utilized LW aggregates made from expanded clay soil.

The water absorption percentages of sand and LW Leca aggregates were 1.4 and 6%, respectively, according to ASTM C128 standard. According to the performed test, the sand surface moisture used in this research was 5.4% and based on ASTM D2216-90 standard.

2.1.4.2 Waste glass powder

Table 5 shows the varied sizes of waste glass utilized in the specimens that included glass powder. Table 6 shows the chemical composition and physical qualities of waste glass, which was made up of a mix of window glass waste and canned glass in this investigation. The waste glass powder is used as a partial substitute for fine aggregates.
in 3 dosages: 20, 25, and 30%. The used waste glass powder is illustrated in Figure 4.

### 2.1.5 Fibers

Fibers are one of the most critical materials used in the present research. In this study, macro-synthetic fibers were used (FORTA Ferro-Green). The Forta-Green blend consists of 100% recycled PP fibrillated (network) fibers and a high-performance twisted-bundle macro-monofilament fiber. The fibers used in this study are with different dosages and combinations, which are specified in Table 8.

**Figure 4**: Samples per gradation of waste glass powder.

**Table 7**: The specifications of the fiber

| Properties                          | Barchip 48          |
|-------------------------------------|---------------------|
| Name                                | Forta Ferro-Green   |
| Length (mm)                         | 54                  |
| Specific gravity                    | 0.91                |
| Tensile strength (MPa)              | 570–660             |
| Melting point (°C)                  | 160                 |
| Material                            | Recycled PP         |
| Form                                | Monofilament/fibrillated |
| Color                               | Gray/dark gray      |
| Acid/alkali resistance              | Excellent           |
| Absorption                          | Nil                 |

**Table 8**: Concrete mix design

| No. | Name  | Fiber (%) | Glass powder (%) | Nanosilica (%) | W/C | Cement (kg/m³) | Aggregate (kg/m³) | Filler (kg/m³) | Leca (kg/m³) | Superplasticizer (kg/m³) |
|-----|-------|-----------|------------------|----------------|-----|----------------|------------------|---------------|-------------|--------------------------|
| 1   | F0g0n0| 0         | 0                | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 2   | F0g0n1| 0         | 0                | 1              | 0.4 | 484            | 533.33           | 177.7         | 266.6       | 2.66                     |
| 3   | F0g0n2| 0         | 0                | 2              | 0.4 | 479.1          | 533.33           | 177.7         | 266.6       | 2.66                     |
| 4   | F0g0n3| 0         | 0                | 3              | 0.4 | 474.2          | 533.33           | 177.7         | 266.6       | 2.66                     |
| 5   | F0.5g0n0| 0.5     | 0                | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 6   | F1g0n0| 1         | 0                | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 7   | F1.5g0n0| 1.5    | 0                | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 8   | F0g20n0| 0         | 2                | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 9   | F0g25n0| 0         | 25               | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 10  | F0g30n0| 0         | 30               | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 11  | F1.5g25n3| 1.5    | 25               | 3              | 0.4 | 474.2          | 533.33           | 177.7         | 266.6       | 2.66                     |
| 12  | F1.5g25n0| 1.5    | 25               | 0              | 0.4 | 488.88         | 533.33           | 177.7         | 266.6       | 2.66                     |
| 13  | F1.5g25n3| 1.5    | 0                | 3              | 0.4 | 474.2          | 533.33           | 177.7         | 266.6       | 2.66                     |
| 14  | F0g25n3| 0         | 25               | 3              | 0.4 | 474.2          | 533.33           | 177.7         | 266.6       | 2.66                     |

The symbol “n” represents the quantity of nanosilica, the letter “f” represents the percentage of used fiber, and the letter “g” represents the percentage of used glass in the concrete.
The fibers are used following ASTM C1116 standard. The fiber’s properties are given in Table 7. Moreover, in Figure 5, FORTA Ferro-Green is shown.

2.2 Concrete mix design

The materials described above were combined using the weight ratio given in Table 8 in accordance with ACI 213-R30. The dry materials were combined first in the mixer, then the water and superplasticizer were progressively added. The water–cement ratio (W/C) was attempted to be kept at 0.4 in this mix design. All specimens have a specific weight of 1,600–1,650 kg/m³.

2.3 Characteristics of the specimens

In this section, the number of specimens made and their characteristics are given in Table 9.

### Table 9: Specification of compressive specimens

| No. | Name    | Fiber (%) | Waste glass (%) | Microsilica (%) |
|-----|---------|-----------|-----------------|-----------------|
| 1   | F0g0n0  | 0         | 0               | 0               |
| 2   | F0g0n1  | 0         | 20              | 0               |
| 3   | F0g0n2  | 0         | 25              | 0               |
| 4   | F0g0n3  | 0         | 30              | 0               |
| 5   | F0.5g0n0| 0         | 0               | 8               |
| 6   | F1g0n0  | 0         | 0               | 10              |
| 7   | F1.5g0n0| 0         | 0               | 12              |
| 8   | F0g20n0 | 0         | 20              | 8               |
| 9   | F0g25n0 | 0         | 20              | 10              |
| 10  | F0g30n0 | 0         | 20              | 12              |
| 11  | F1.5g25n3| 0        | 25              | 8               |
| 12  | F1.5g25n0| 0        | 25              | 10              |
| 13  | F1.5g25n3| 0        | 25              | 12              |
| 14  | F0g25n3 | 0         | 30              | 8               |

### Table 10: Compressive strength test results

| No. | Name    | 7 days (MPa) | 28 days (MPa) | Slump (mm) |
|-----|---------|--------------|---------------|------------|
| 1   | F0g0n0  | 30.1         | 38            | 68         |
| 2   | F0g0n1  | 34.2         | 43            | 59         |
| 3   | F0g0n2  | 39.1         | 49            | 57         |
| 4   | F0g0n3  | 44.3         | 56            | 54         |
| 5   | F0.5g0n0| 30          | 38.7          | 51         |
| 6   | F1g0n0  | 31.6         | 39.4          | 42         |
| 7   | F1.5g0n0| 32.5         | 40.7          | 66         |
| 8   | F0g20n0 | 32.7         | 41            | 58         |
| 9   | F0g25n0 | 37.5         | 47            | 55         |
| 10  | F0g30n0 | 36.2         | 45            | 52         |
| 11  | F1.5g25n3| 51        | 64            | 49         |
| 12  | F1.5g25n0| 38.7        | 48.2          | 44         |
| 13  | F1.5g25n3| 45.6        | 57.3          | 67         |
| 14  | F0g25n3 | 49.9         | 62.3          | 60         |

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Figure 5: (a) Shape of fibers and (b) fiber length.
10 cm × 20 cm were prepared. For each combination, 3 specimens with ages of 7 and 28 days were made and tested.

3 Test results

3.1 Compressive strength test

After averaging the findings of the compressive specimens, they are shown here. According to the ASTM C143 standard, the slump test has been carried out. The compressive strength and slump test results for cube specimens are shown in Table 10. The average weight of the dried specimens was between 5.2 and 5.5 kg.

As can be observed from Figure 6, with increase in the consumption of nanosilica, the 28-day compressive strength of the specimens increased, so that by replacing 3% nanosilica instead of cement, the compressive strength of the concrete specimen increased by 47% compared to that of control. By adding glass powder instead of fine particles, the compressive strength of the specimen increases.

Glass powder should be used at an optimum of 25%. Compressive strength increases by 23% when 25% glass powder is used. For the most part, recycled fibers did not influence the samples' compressive strength, but they did have an impact on their ductility. Compressive strength is increased by 7% when fiber cement weight is included in the mix at a rate of 1.5%. The highest compressive strength is related to the F1.5g25n3 specimen. The combination of fibers, glass powder, and nanosilica has increased the compressive strength by 68%. Nanosilica and glass powder have been able to increase the specimen compressive strength by filling the empty space of the concrete mixture and affecting the hydration process.

3.2 Scanning electron microscopy (SEM) analysis

The findings of a SEM test were used to examine the concrete's microscopic structure and the impact of adding glass powder and nanosilica on the mix. Figure 7 shows the SEM analysis.

In Figure 8, X refers to the structure of nanosilica as determined by the IDFiX report test. It can be observed that nanosilica particles and glass powder are well dispersed in the concrete matrix and have increased the strength of concrete due to their adhesion properties.

3.3 Tensile strength test

The results of the tensile strength test are shown in Table 11. This test was performed for all 14 specimens at the ages of 7 and 28 days. In Figure 9, tensile strength specimen is shown.
As can be observed in Figure 10, with the addition of fibers, the tensile strength of the specimens increased significantly. Also, with the addition of nanosilica and glass powder, the tensile strength of the samples increased. The best tensile strength of the specimen contains 1.5% of fibers, 3% of nanosilica, and 25% of glass powder, so its 28-day tensile strength is 1.6 times that of the control specimen.

4 Life cycle assessment (LCA)

Due to the rapid development of the building industry and the exponential growth of the construction sector, the consequences of boundless human interventions in the environment gradually became apparent, and subsequently, efforts were made to preserve living conditions. One of the best ways to improve the properties of concrete

Figure 7: SEM test: (a) concrete specimens containing 25% glass powder and 3% nanosilica and (b) change in the direction of crack movement due to the presence of glass powder.
from an environmental point of view is to find suitable alternatives to the cement used in concrete. Meanwhile, pozzolans, which have long been used as a substitute and complement to cement in construction, can solve the problems related to production limitation to a large extent. Pozzolans have increased their compressive strength and durability by replacing a part of cement while saving energy consumption required in cement production and reducing pollutant emissions.

With the advent of nanotechnology, nanosilica has become one of the most critical nanoparticles with high pozzolanic properties in concrete that require high resistance to corrosion and abrasion or in cases where the use of pavement concrete has been used. In this article, mix design number 11 has been selected as the best mixing.

Table 11: Tensile strength

| No. | Name    | 7 days (MPa) | 28 days (MPa) |
|-----|---------|--------------|---------------|
| 1   | F0g0n0  | 2.15         | 2.65          |
| 2   | F0g0n1  | 2.42         | 3.29          |
| 3   | F0g0n2  | 2.81         | 3.63          |
| 4   | F0g0n3  | 3.18         | 4.36          |
| 5   | F0.5g0n0| 2.11         | 2.73          |
| 6   | F1g0n0  | 2.3          | 2.91          |
| 7   | F1.5g0n0| 2.64         | 3.43          |
| 8   | F0g20n0 | 3.1          | 4.03          |
| 9   | F0g25n0 | 2.61         | 3.38          |
| 10  | F0g30n0 | 2.5          | 3.18          |
| 11  | F1.5g25n3| 3.65        | 5.1           |
| 12  | F1.5g25n0| 2.6         | 3.47          |
| 13  | F1.5g25n3| 3.28        | 4.4           |
| 14  | F0g25n3 | 2.9          | 4.1           |

Figure 8: IDFIX report test diagram related to nanosilica.

Figure 9: Tensile strength test machine.

Figure 10: Comparison of tensile strength.
design. Using this mix design, cement consumption has been reduced by 3%, and nanosilica has been used instead.

The LCA consists of four main stages: (1) Goal and scope definition. (2) Inventory analysis. (3) Impact assessment. (4) Interpretation. According to the ISO 14040 standard, the first step in LCA is reviewing the goal and scope definition. In this article, two scenarios are defined by determining the construction of one cubic meter of concrete for application in a residential structure with a useful life of 50 years. The first scenario is concrete with mixing design number 1 and the second scenario is concrete with mixing design number 11. AkzoNobel company [42] published a report on environmental performance in 2020. According to this report, Table 12 examines energy use and emissions for both the scenarios.

As shown in Table 12, replacing cement with 3% nanosilica can reduce energy usage, greenhouse gas emissions, freshwater usage, and producing hazardous waste non-reusable by 3%, which helps to make sustainable concrete.

Also, using discarded glass powder and PP fibers simultaneously may reduce CO₂ emissions. Cutright et al. investigated the impact of utilizing PP fibers instead of steel rebar to decrease CO₂ emissions [43]. Four steel rebars @12 are used to construct a roof with a thickness of approximately 20 cm; the quantity of CO₂ emission is 3.35 kg for 1 m² concrete. When PP fibers are used, this quantity decreases to 1.47 kg. Table 13 shows the quantity of CO₂ released during construction of a 5-story, 300 m² structure [38].

5 Conclusion

The following results were obtained after performing experiments on cubic specimens and examining microscopic images.

1. According to the findings in the literature, the compressive strength increases as the amount of nanosilica increases. The specimen with the best compressive strength contains 3% nanosilica and has a 28-day compressive strength that is 47% higher than that of the control specimen.
2. The highest amount of waste glass powder is 25%, and the compressive strength of concrete reduces with increased use due to its brittleness. The specimen containing 25% waste glass powder has a compressive strength that is 24% higher than that of the control specimen.
3. The compressive strength increases as the amount of recycled PP fibers used increases. The specimen with 1.5% fibers had the highest use rate, increasing the strength by 7% when compared to the control specimen. The fibers have no influence on the compressive strength of concrete, but they do contribute significantly to its ductility.
4. The best tensile strength is achieved by 1.5% of fibers, 3% of nanosilica, and 25% of waste glass powder, so its 28-day tensile strength is 1.6 times that of the control sample.
5. Simultaneous use of nanosilica, waste glass powder, and recycled fibers in LW concrete can increase its compressive strength. As a result, the compressive strength of the specimen, including 1.5% fibers, 3% nanosilica, and 25% glass powder, is 68% higher than that of the control specimen. Recycled glass powder collects this type of waste from the environment while also contributing to the sustainability of aggregates’ natural resources. Nanosilica is a sustainable material that helps to reduce the quantity of cement used. Recycled fibers are also entirely eco-friendly because they are manufactured from recycled resources. The use of this green material minimizes the amount of CO₂ released into the atmosphere.

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