International Journal of Researches on Civil Engineering with Artificial Intelligence

www.ceai.reapress.com

Int. J. Res. Civ. Eng. AI. Vol. 3, No. 3 (2026) 177–199.

Paper Type: Original Article

Investigating the Properties of Fresh and Hardened Concrete Containing Recycled Aggregates Using Magnetized Water

Rahmat Madandoust[1,*], Zahra Shapouri[1]

[1] Department of Civil Engineering, Technical College, University of Guilan, Rasht, Iran; rmadandoust@guilan.ac.ir; zahrashapoury@gmail.com.

Citation:

Received: 25 August 2025 *Revised: 19 November 2025* *Accepted: 13 January 2026*	Madandoust, R., & Shapouri, Z. (2026). Investigating the properties of fresh and hardened concrete containing recycled aggregates using magnetized water. *International journal of researches on civil engineering with artificial intelligence, 3*(3), 177-199.

Abstract

In this research, the properties of fresh and hardened concrete containing recycled aggregates are investigated using magnetized water.in this technohogy, by including a magnetic field into water, its physical structure changes.as a result of these changes, the number of molecules in molecular aggregation has reached 5 or 6 from 13 and the surface tension of water decreases. The uses of this processed water in concrete, on the one hand, increases the fluidity of the concrete mixture and ewduces the required water, and on the other hand, by facilitating the hydration of cement, it improves the strength of concrete.it is obtained from breaking and crushing construction refuse. In this research, the mechanical properties of concrete, including compressive, tensile, and bending strength, have been investigated. These variables include the number of different cycles of water in the magnetic field, different amounts of super plasticizer, steel fibers and microsilica.in total, samples were made in 11 different esigns with and without fibers. It should be noted that half of the mentioned samples have steel fibers.the results of most of the tests showed that although magnetic water has an effect on the mechanical properties of concrete, it should not be used alone as a compensating agent for defects caused by recycled aggregates. The use of microsilica along with magnetic water greatly improves the properties of concrete.also, for the effect of magnetic water with a field strength of 1.2 Tesla, samples with tap water have also been made.the results obtained from fresh concrete in the laboratory show that the magnetic water and pozzolan used improve the condition of concrete in terms of fluidity and viscosity. Based on this, magnetic water can reduce the amount of water required for concrete. The results of hardened concrete also indicate the improvement of the resistance properties of concrete containing magnetic water and pozzolan.based on this, it is possible to choose the mixing design including ten rounds of magnetic water and 10% replacement of microsilica with a 40% and 25% increase in compressive strength and tensile strength, as well as a 35% increase in bending strength.

Keywords: Properties of fresh concrete, Properties of hardened concrete, Recycled aggregates, Magnetic water.

1 | Introduction

The increasing consumption of natural resources and the large amount of construction waste generated have become among the major environmental concerns facing human societies. Therefore, extensive efforts have

Corresponding Author: rmadandoust@guilan.ac.ir

https://doi.org/10.48314/ijrceai.vi.62

been made in industrialized countries to reduce the disposal of construction waste into the environment. One of the effective approaches is the reuse of demolished materials in the production of concrete. This method not only decreases the amount of waste transported to landfills and reduces the extraction of natural resources but also creates new employment opportunities in the construction market [1], [2].

Based on the extensive preliminary studies conducted on recycled aggregates, including the investigations carried out, significant differences exist between the physical characteristics of recycled concrete aggregates and natural aggregates. These differences include higher porosity, lower density, and greater water absorption capacity. They also reported that recycled aggregates generally experience higher levels of abrasion and crushing compared with natural aggregates. The incorporation of such aggregates into concrete results in materials with lower quality than conventional concrete produced with natural aggregates. In addition, the strength decreases while permeability increases [3–5].

The use of magnetic water in concrete mixtures has been reported to improve concrete slump properties [6], [7]. Magnetic water is produced by passing water through a magnetic field. The magnetic characteristics of water increase as the intensity of the generated magnetic field becomes stronger. The applied magnetic field can also influence the number of hydrogen bonds between water molecules [8–10].

The application of magnetic water allows a reduction in the required amount of superplasticizer while maintaining the same water-to-cementitious materials ratio. In this study, magnetic water technology was applied along with different concrete mixtures containing recycled aggregates, micro-silica, and superplasticizer to enhance the mechanical performance of recycled aggregate concrete. The experimental investigations included slump test, compressive strength, tensile strength, flexural strength, water absorption, and density measurements. A total of 11 concrete mix designs were prepared and evaluated.

The main objective of this research is to utilize recycled aggregates as both fine and coarse aggregates in fresh and hardened concrete containing magnetic water. Magnetic fields can affect the properties of water, and researchers have investigated the potential influence of magnetic treatment on water characteristics for many years. In simple terms, water exposed to a magnetic field can exhibit magnetic properties, although this induced magnetism is relatively weak.

Considering the widespread application of concrete in construction, numerous studies have investigated the influence of magnetic water on concrete properties. The present research aims to introduce the concept of magnetic water and provide a review of previous studies conducted in this field.

In this study, the properties of fresh and hardened concrete containing recycled aggregates and produced using magnetic water were investigated. Furthermore, through laboratory-prepared mixtures and concrete specimens, the effects of magnetic water on various concrete properties, including compressive strength, tensile strength, and other mechanical characteristics, were evaluated.

Matthias et al. [11] reported that the shape and morphology of recycled aggregates significantly affect the performance and properties of concrete. Recycled aggregates produced through conventional crushing methods generally have a more rounded shape compared with natural aggregates due to the weakness of the attached old mortar. The use of rounded recycled aggregates instead of angular aggregates may indirectly improve some concrete properties because angular aggregates require higher amounts of cement paste and water. Furthermore, their irregular shape may negatively affect concrete strength and durability. The density of concrete depends on the density of its constituent aggregates; therefore, larger and heavier aggregates generally result in higher concrete density. Increasing the amount of mortar content reduces concrete density while increasing porosity and water absorption capacity. Evaluating the water absorption of recycled aggregates is essential because it can influence concrete strength and performance. The use of superplasticizers can partially compensate for the reduction in compressive and tensile strength of recycled aggregate concrete; however, their efficiency remains lower compared with concrete containing natural aggregates. High-performance superplasticizers have a greater impact on improving the efficiency and strength of this type of concrete. Since recycled aggregates possess a rougher surface texture than conventional aggregates, they provide stronger adhesion with cement paste, which can improve tensile strength. Nevertheless, increasing the amount of recycled aggregate in the mixture may reduce tensile strength, which can be partially compensated by adding superplasticizers. Finally, superplasticizers do not significantly influence the abrasion resistance of concrete.

Dutta et al. [12] investigated various characteristics of recycled aggregate concrete and concluded that increasing the replacement ratio of natural aggregates with recycled aggregates leads to a reduction in compressive strength and elastic modulus while increasing drying shrinkage. Their economic analysis also indicated that the use of recycled aggregates in concrete production can provide economic benefits when suitable sources for recycled aggregate production are available.

Xiao et al. [13] investigated recycled aggregate concrete in China during the period from 1996 to 2011 and reported several important findings. Regarding the microstructural characteristics, they observed that recycled concrete has a more complex structure compared with conventional concrete. This type of concrete contains two interfacial transition zones: the interface between the original aggregate and old cement mortar, and the interface between recycled aggregate and newly formed cement mortar.

According to the studies conducted by Su et al. [14] and investigations performed in several industrialized countries, including Russia and China, the use of magnetic water in concrete production can improve efficiency, increase compressive strength, and enhance concrete permeability characteristics. Moreover, because magnetic water increases concrete strength, it may reduce cement consumption without requiring additional additives. This reduction in cement usage can contribute to lowering cement production and its associated environmental impacts. These researchers also investigated the effect of using blast furnace slag in concrete produced with magnetic water treated under different magnetic fields. They concluded that applying magnetic fields with intensities of 0.8, 1.2, and 1.35 Tesla increased concrete compressive strength by approximately 9–19%. They further reported that the use of magnetic water in mixtures containing blast furnace slag improved performance compared with conventional water. According to their findings, the strength improvement caused by magnetic water in ordinary concrete ranges between 10% and 23%.

Toledo et al. [15] reported that exposing water to a magnetic field increases its evaporation rate. They concluded that magnetic fields affect the number of hydrogen bonds present between water molecules.

The investigations conducted by Karam and Shameli [16] demonstrated that concrete produced with magnetic water exhibited a 10–15% increase in compressive strength compared with concrete prepared using ordinary water.

2 | Characteristics of Materials Used in the Experimental Program

The materials used for conducting the experiments in this study are described as follows.

2.1 | Cement

The cement used in all experiments was sulfate-resistant Portland cement (Type II) supplied by Abyek Cement Factory. Based on the conducted tests, all properties of the cement complied with the required standard specifications.

2.2 | Micro-Silica

The micro-silica used in this research was supplied by Jikava, one of the manufacturers of concrete admixtures, under the commercial name Micro Silica. The material complied with ASTM C1240 requirements. It was available as a gray powder with a specific gravity of 13.2 g/cm^3 and supplied in 5 kg packages.

2.3 | Aggregates

2.3.1 | Natural coarse aggregates

The natural aggregates used in the control mixture designs consisted of crushed aggregates (*Fig. 1*), which were obtained from the aggregate storage area located in the laboratory throughout the experimental program.

Fig. 1. Natural coarse aggregates.

2.3.2 | Recycled coarse aggregates

The recycled aggregates required for the experimental investigations were obtained from the Concrete Quality Control Laboratory (*Fig. 2*). These aggregates were used in all concrete mix designs that contained recycled aggregate. Since the primary objective of this research was to compare the performance of natural and recycled aggregates, 100% recycled aggregates were utilized in the relevant mixtures to achieve more accurate and reliable experimental results.

Fig. 2. Recycled coarse aggregates.

Due to the wide particle size distribution of the initial aggregate stockpile, the grading of the materials was manually adjusted. It should be noted that, in order to achieve a more accurate comparison between the experimental results and the control specimens, the recycled aggregate grading was prepared according to the grading distribution of the natural aggregates. This approach was adopted to provide a relatively uniform aggregate distribution and ensure more reliable comparisons. The results obtained from the sieve analysis of the recycled aggregates are presented in *Fig. 3*.

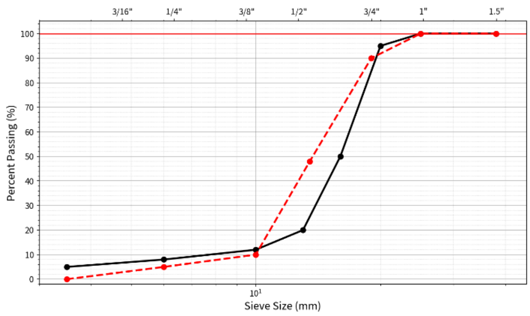


Fig. 3. Particle size distribution curve of recycled aggregates and its comparison with the mandatory standard requirements.

Sand grading

The particle size distribution of the sand aggregates was determined using a complete set of standard sieves. The obtained grading results are fully presented in *Fig. 4*.

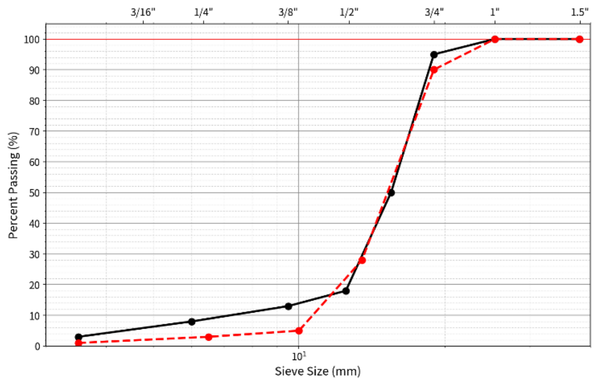


Fig. 4. Particle size distribution curve of sand and its comparison with standard requirements.

Similar to the sand aggregates, the results of the additional tests performed on the coarse aggregates are presented in *Table 1*.

Table 1. Results of the tests conducted on coarse aggregate.

Type of Coarse Aggregate	Specific Gravity (gr/cm³)	Water Absorption (SSD)	Los Angeles Abrasion
Natural	2.65	1.28	10.21
Recycled	2.21	7.92	32.73

2.4 | Aggregate (Fine Aggregate/Sand)

The sand used in all mix designs was natural, washed sand, obtained from the stockpile located in the laboratory and used throughout the experimental program.

2.4.1 | Particle size distribution of sand

The results of the sand sieve analysis were plotted on the particle size distribution (gradation) curve using standard sieves and compared with the limits specified in the Iranian National Standard. *Fig. 5* presents the sand gradation curve together with its comparison against the mandatory requirements of the standard for fine aggregate (sand).

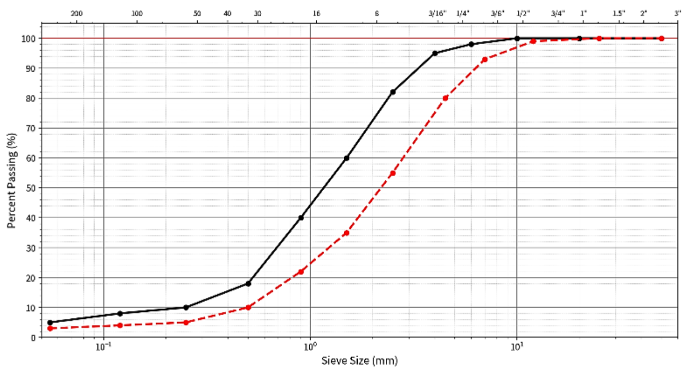


Fig. 5. Particle size distribution (gradation) curve of the sand and its comparison with the mandatory requirements of the standard for fine aggregate.

Based on the results of the sieve analysis, the Fineness Modulus (FM) of the sand was 2.7.

In addition, several supplementary laboratory tests were conducted on both the coarse and fine aggregates. The results of these tests are presented in *Table 2*.

Table 2. Results of the tests performed on sand.

Specific Gravity	Water Absorption (SSD)	FM
2.6	3.6	2.7

2.5 | Superplasticizer

The superplasticizer used in this study was a High-Range Water-Reducing Admixture (HRWR) based on modified polycarboxylate polymers. It is suitable for producing highly flowable and self-compacting concrete without the need for additional mixing water or causing aggregate segregation. The admixture is compatible with all types of cement and complies with ASTM C494.

In this study, different dosages of the superplasticizer were used to achieve the target slump corresponding to the use of magnetized water. The optimum dosage was determined through a series of trial-and-error laboratory tests.

2.6 | Magnetized Water

Extensive studies have been conducted to produce magnetized water, and various devices have been evaluated for this purpose. In the present study, a device was employed in which water passes through both a static magnetic field and an electromagnetic field, thereby acquiring magnetic properties. The resulting water was passed through a magnetic field with a flux density of 1.2 T (Tesla) to produce magnetized water. *Figs. 6* and *7* illustrate the magnetized water generation device.

According to the study by Ahmed [17], magnetized water passed ten times through the magnetic field at the lowest flow velocity produced the optimum improvement in concrete strength. Therefore, in the present study, both single-pass and ten-pass magnetized water were used to properly evaluate the effect of magnetized water on the properties of concrete.

Fig. 6. Magnetized water generation device.

Fig. 7. Magnetized water generation device.

2.7 | Steel Fibers

The steel fibers used in this study were hooked-end steel fibers manufactured by the Italian company Durochem. Owing to the limited number of manufacturers producing this type of fiber, its use is relatively uncommon. Consequently, the product is comparatively expensive in Iran.

The physical properties of the steel fibers are presented in *Table 3*, while their appearance is shown in *Fig. 8*.

Fig. 8. Double-end hooked steel fibers.

Table 3. Properties of steel fibers.

Specific Weight	Tensile Strength	Length	Diameter	Aspect Ratio
7.85 gr/cm^3	809 N/mm^2	50 mm	0.8 Mm	5.62

According to the study conducted by Ramezani et al. [18], among concrete specimens containing 0.25%, 0.50%, 0.75%, and 1.0% steel fibers, the specimens reinforced with 1.0% steel fibers exhibited the best overall performance. These specimens achieved the highest compressive and splitting tensile strengths. Therefore, 1.0% steel fibers were adopted in the present study.

3 | Mix Design

One of the most important stages in preparing the experimental program is the selection of an appropriate concrete mix design. The mix proportions used in this study were designed in accordance with ACI 211, and the same base mix was maintained throughout all experiments to ensure a reliable comparison of the test results.

The selected mix design was developed with a constant water-to-binder ratio (w/b) of 0.50, allowing the effect of magnetized water to be clearly observed. Using a mix with a lower water-to-binder ratio would reduce the ability to distinguish the influence of magnetized water on concrete properties.

Control mixtures C1 and C2 in the first experimental series were designed to clearly evaluate the effect of magnetized water on concrete made with natural aggregates. In addition, control mixture C3, which contained recycled aggregates without any admixtures, was prepared to determine the influence of recycled aggregates on the properties of concrete.

Overall, the first series of mixtures served as the control group and provided a basis for comparison with the remaining mixtures. The second and third series were identical except that the third series incorporated silica fume. This arrangement enabled a more accurate evaluation of the effect of silica fume on the experimental results, as well as the influence of magnetized water on concrete containing this supplementary cementitious material. Since silica fume particles are significantly finer than cement particles, they are expected to exhibit a more pronounced interaction with magnetized water.

Furthermore, in both the second and third series, a superplasticizer was used at dosages that produced slump values equivalent to those obtained using single-pass and ten-pass magnetized water, enabling a direct comparison between the effects of the superplasticizer and those of magnetized water.

Table 4. Selected mix proportions for concrete mixtures without steel fibers (per cubic meter).

Mix Name/Mix Design Mix Name/Mix Design	Cement (kg)	Water (kg)	Magnetic Cycles	Aggregate			Superplasticizer (kg)	Silica Fume (kg)
				Fine Aggregate	Coarse Aggregate			
				Fine Aggregate	Recycled Aggregate	Natural Aggregate		
C1	386	193	-	900	0	821	0	0
C2	386	193	5	900	0	821	0	0
C3	386	193	-	0	900	821	0	0
W1	386	193	1	0	900	821	0	0
W2	386	193	10	0	900	821	0	0
S1	386	193	-	0	900	821	2.9	0
S2	386	193	-	0	900	821	3.5	0
WF1	347.4	193	1	0	900	821	0	38.6
WF2	347.4	193	10	0	900	821	0	38.6
SF1	347.4	193	-	0	900	821	3.2	38.6
SF2	347.4	193	-	0	900	821	3.86	38.6

The mix design adopted in this study for steel fiber-reinforced concrete was largely identical to the mix design used for concrete without fibers (*Table 4*). The only difference was the incorporation of 1.0% steel fibers by concrete volume, corresponding to 78.5 kg/m^3, which were added during the mixing process.

One of the most important parameters in concrete mix design is the water-to-cement ratio (w/c). In this study, all mix design calculations were performed based on the Saturated Surface-Dry (SSD) condition of the aggregates. Under the SSD condition, the aggregates are assumed to neither absorb water from nor contribute water to the concrete mixture.

If the moisture content of the fine aggregate differs from the SSD condition, appropriate corrections must be made to both the aggregate mass and the mixing water. However, because such corrections may reduce measurement accuracy and introduce additional experimental errors, they are generally avoided. Instead, the natural moisture content of the aggregates is determined prior to each trial mix, and the required adjustments are made accordingly.

Consistent with the selected mix design, a water-to-cement ratio of 0.50 was adopted throughout this investigation. This value was selected because it is commonly used in conventional concrete production and allows the influence of magnetized water on the concrete properties to be clearly observed. Lower water-to-cement ratios tend to reduce the observable effect of magnetized water.

3.1|Specimen Designation

A total of 11 different concrete mixtures were prepared in this study. Three mixtures were used as control specimens, while the remaining eight mixtures were designed to evaluate the effect of magnetized water on concrete containing recycled aggregates. All mixtures were proportioned to achieve the same target slump for conventional concrete. The designation and description of the specimens are presented in *Table 5*.

Table 5. Identification of concrete specimens.

No/ Row	Descriptions	Superplasticizer	Silica Fume	Water Type	Aggregate type	Mix Name /Mix Design Name
1	Containing natural aggregates and conventional water.	×	×	TW	NA	C1
2	Containing natural aggregates and five-pass magnetized water.	×	×	MW	NA	C2
3	Containing recycled aggregates and conventional water.	×	×	TW	RA	C3

Table 5. Continued.

No/ Row	Descriptions	Superplasticizer	Silica Fume	Water Type	Aggregate type	Mix Name / Mix Design Name
4	Containing recycled aggregates and water that has passed through the magnetic field device once.	×	×	MW	RA	W1
5	Containing recycled aggregates and water that has passed through the magnetic field device ten times.	×	×	MW	RA	W2
6	Containing recycled aggregates, conventional water, and a specific amount of superplasticizer to achieve a slump equivalent to W1.	+	×	TW	RA	S1
7	Containing recycled aggregates, conventional water, and a specific amount of superplasticizer to achieve a slump equivalent to W2.	+	×	TW	RA	S2
8	Containing recycled aggregates and one-pass magnetized water, with 10% replacement of cement by silica fume.	×	+	MW	RA	WF1
9	Containing recycled aggregates and ten-pass magnetized water, with 10% replacement of cement by silica fume.	×	+	MW	RA	WF2
10	Containing recycled aggregates, conventional water, 10% replacement of cement with silica fume, and a specific amount of superplasticizer to achieve a slump equivalent to S1.	+	+	TW	RA	SF1
11	Containing recycled aggregates, conventional water, 10% replacement of cement with silica fume, and a specific amount of superplasticizer to achieve a slump equivalent to S2.	+	+	TW	RA	SF2

4 | Experimental Program

4.1 | Compressive Strength Test

Since compressive strength is one of the most important properties of hardened concrete and serves as the primary criterion for concrete classification in international standards, its evaluation is of particular importance.

Several standards are available for conducting compressive strength tests. One of the most widely used is BS EN 12390-3:2009, which was originally published in 2002 and revised in 2011. It has since been reissued in several editions under the same designation. Another commonly adopted standard is ASTM C39/C39M, which specifies the use of cylindrical concrete specimens for compressive strength testing. However, due to practical considerations associated with the experimental program, the European Standard (BS EN 12390-3) was selected instead of ASTM C39/C39M for this study.

A total of 66 concrete cube specimens with dimensions of 150 × 150 × 150 mm were prepared for the compressive strength tests. These specimens were produced from 11 different concrete mixtures. For each mixture, three specimens containing steel fibers and three specimens without steel fibers were cast. The average compressive strength was calculated from the results of the three identical specimens.

4.2 | Splitting Tensile Strength Test

The splitting tensile strength (Brazilian tensile) test was performed in accordance with ASTM C496/C496M. Following the requirements of this standard, cylindrical specimens with a diameter of 150 mm and a length of 300 mm were used.

The specimens were water-cured for 28 days and subsequently placed in an oven for approximately 2–3 hours to ensure that their surfaces were completely dry before testing.

For testing, each specimen was placed horizontally between the loading platens of the testing machine. An additional loading strip (or bearing plate) was positioned on top of the specimen to ensure a uniform distribution of the applied load. Care was taken to align the specimen precisely at the center of the lower loading platen so that the load was applied uniformly along its length. Figure 9 illustrates the positioning of the specimen in the testing machine.

Fig. 9. Arrangement of the concrete specimen and loading strips between the loading platens of the testing machine for the Brazilian splitting tensile strength test.

4.3 | Flexural Strength Test

In this study, the flexural strength test was conducted as one of the principal mechanical tests in accordance with ASTM C1018 and its specified requirements. The preparation, dimensions, and handling of the specimens were carried out in accordance with ASTM C31/C31M and ASTM C192/C192M.

Accordingly, prismatic specimens with dimensions of 100 × 100 × 350 mm were cast. After 28 days of water curing, the specimens were placed in an oven for approximately 2–3 hours to ensure that they were completely dry prior to testing.

Before the flexural test, each specimen was positioned on the supports so that the top and bottom surfaces corresponded to the orientation in which the specimen had been cast. For shotcrete specimens, if applicable, the specimen was placed in the testing machine with the sprayed surface oriented in accordance with the requirements of the standard.

Following completion of the flexural test, the performance of the steel fiber-reinforced concrete specimens was evaluated using the procedures specified in ASTM C1018, JSCE-SF4 (JSCE 59), and the PCS (Post-Crack Strength) method.

The loading configuration and test setup are illustrated in *Fig. 10*.

Fig. 10. Loading configuration for the flexural strength test.

5 | Results and Discussion

5.1 | Compressive Strength Test Results

The results of the 28-day compressive strength tests conducted on the concrete cube specimens corresponding to the 11 different mix designs are presented in *Table 6*.

Table 6. Results of the 28-day compressive strength tests for concrete cube specimens with and without steel fibers (MPa).

No.	Mix Design Name	Fiber-Reinforced Specimens' Tensile Strength (MPa)	Tensile Strength of Non-Fiber-Reinforced Specimens (MPa)
1	C1	36.7	34.98
2	C2	39.48	37.81
3	C3	20.88	20.30
4	W1	24.00	22.42
5	W2	26.98	25.65
6	S1	25.90	22.50
7	S2	23.75	21.83
8	WF1	33.61	29.90
9	WF2	35.00	32.74
10	SF1	33.57	30.68
11	SF2	33.52	31.17

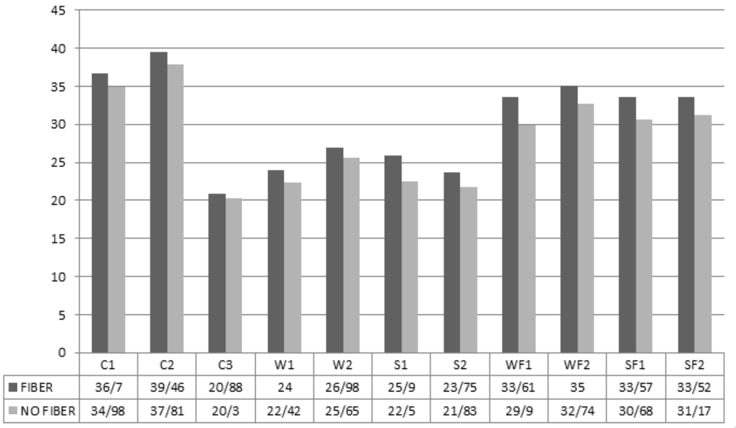


Fig. 11. Compressive strength test results of specimens with and without steel fibers (MPa).

Table 7. Compressive strength test results of equivalent cylindrical specimens with and without steel fibers (MPa).

No.	Mix Design Name	Equivalent 28-Day Compressive Strength of Cylinder Specimens	
		Fiber-Reinforced Specimens' Tensile Strength (MPa)	Tensile Strength of Non-Fiber-Reinforced Specimens (MPa)
1	C1	30.09	28.68
2	C2	32.36	31.00
3	C3	17.12	16.65
4	W1	16.68	18.38
5	W2	22.12	21.03
6	S1	21.24	18.45
7	S2	1948	17.90
8	WF1	27.56	24.52
9	WF2	28.70	26.85
10	SF1	27.53	25.16
11	SF2	27.49	25.56

5.1.1 | Analysis of compressive strength test results

Based on *Tables 6* and *7* and *Fig. 11*, it can be observed that, for all mix designs, the compressive strength of the specimens containing steel fibers was higher than that of the corresponding specimens without fibers. Although the increase in compressive strength due to the incorporation of steel fibers was relatively small in some mixtures, the overall results indicate that the inclusion of steel fibers improves the compressive strength of concrete.

However, the enhancement in compressive strength was generally modest. The primary contribution of the steel fibers was observed in the deformation behavior and post-peak response of the concrete during loading. This effect became evident when the specimens were subjected to compressive loading, as the fibers improved crack-bridging and restrained crack propagation. Consequently, the influence of the steel fibers can be clearly identified by comparing the failure patterns of the cube specimens with and without fibers, as illustrated in *Fig. 12*.

Fig. 12. Failure modes of compressive strength specimens: a. without steel fibers, and b. with steel fibers.

Considering that the 28-day compressive strength of the cylindrical concrete specimens in the selected mix design was 25 MPa, the 28-day compressive strength of cylindrical specimens (*Table 7*) can be estimated from the compressive strength results of cube specimens by applying a conversion factor of 0.82.

By examining *Table 4*, it can be observed that five-pass magnetized water increased the compressive strength of the C2 control mixture compared with the C1 control mixture for both fiber-reinforced and non-fiber-reinforced specimens.

It was also observed that the C3 control mixture exhibited the lowest strength among all mixtures. The compressive strength of this mixture was lower than the average strength of the specimens with and without steel fibers; therefore, this mixture cannot be considered acceptable from a safety perspective.

Furthermore, the mixtures S1, S2, W1, and W2, which consisted of single-pass and ten-pass magnetized water and superplasticizer dosages equivalent to the slump obtained with single-pass and ten-pass magnetized water, respectively, did not achieve satisfactory compressive strength. The highest compressive strength among these mixtures was obtained for W2, reaching 26.98 MPa.

Based on the results of the four mixtures WF1, WF2, SF1, and SF2, it can be concluded that these mixtures exhibited the best compressive strength performance. Among them, the lowest compressive strength was observed in the WF1 mixture without steel fibers. In contrast, the highest compressive strength among the recycled aggregate concrete mixtures was obtained for WF2, which contained steel fibers and reached 35 MPa.

Therefore, in general, the combination of silica fume and ten-pass magnetized water (WF2) improved the compressive strength of recycled aggregate concrete, achieving a strength value only slightly lower than that of the C1 control mixture containing natural aggregates and conventional water.

5.2 | Tensile Strength Test Results

The results of the 28-day splitting tensile strength tests conducted on the cylindrical concrete specimens corresponding to the 11 different mix designs are presented in *Table 8* and *Fig. 13*.

Table 8. Results of the splitting tensile strength test of concrete specimens with and without steel fibers (MPa).

No.	Mix Design Name	Fiber-Reinforced Specimens' Tensile Strength (MPa)	Tensile Strength of Non-Fiber-Reinforced Specimens (MPa)
1	C1	4.17	2.58
2	C2	3.91	3.50
3	C3	2.78	1.93
4	W1	3.14	2.27
5	W2	3.33	2.68
6	S1	3.04	2.22
7	S2	3.28	2.44
8	WF1	3.36	2.61
9	WF2	3.74	3.15
10	SF1	3.29	2.92
11	SF2	3.46	3.03

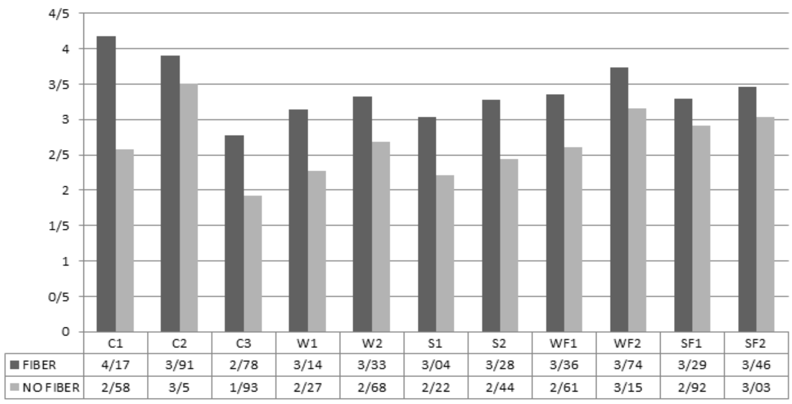


Fig. 13. Tensile strength of concrete mix designs.

5.2.1 | Analysis of Splitting Tensile Strength Test Results

As shown in the above chart, in all mixtures, the specimens containing steel fibers exhibited higher splitting tensile strength compared with the specimens without steel fibers.

In addition, the failure modes of the tensile specimens with and without fibers are presented in the following figure. It should be noted that both types of specimens experience a significant longitudinal crack during failure. However, the main difference is that the specimens containing steel fibers do not separate into two distinct parts even after reaching the ultimate failure load. In contrast, the specimens without steel fibers undergo complete separation after cracking.

Fig. 14 illustrates the failure modes of the specimens 1) with steel fibers, and 2) without steel fibers subjected to the splitting tensile strength test.

a.

b.

Fig. 14. Failure modes of specimens a. with steel fibers and b. without steel fibers under the splitting tensile strength test.

For the C1 and C2 control mixtures, where the only difference between them was the magnetization of the mixing water in mixture C2, the highest tensile strength among the non-fiber-reinforced specimens was obtained for C2. This mixture was produced using natural aggregates and five-pass magnetized water, and its tensile strength was 36% higher than that of C1, which was prepared using conventional water.

However, for the steel fiber-reinforced specimens, the tensile strength of C2 was slightly lower than that of C1. Among the control mixtures, the lowest tensile strength was observed in C3, which was produced using recycled aggregates. This reduction in strength can be attributed to the use of aggregates with significantly lower quality compared with natural aggregates.

The specimens produced with recycled aggregates and one-pass and ten-pass magnetized water (W1 and W2) showed improvements compared with the C3 control mixture. For specimens without fibers, the tensile strength increased by 13% and 18%, respectively, while for specimens containing steel fibers, the increase was 18% and 39%, respectively.

This improvement indicates that the application of magnetized water technology can provide higher tensile strength than conventional concrete produced with natural aggregates. It is also worth noting that, when comparing specimens prepared with conventional water and superplasticizer with those produced using magnetized water, the effect of replacing conventional water and superplasticizer with magnetized water was more significant.

The improved uniformity of concrete produced with magnetized water, along with the higher workability of this concrete, justifies the selection of magnetized water over conventional water combined with a superplasticizer in mixtures without silica fume.

For mixtures containing silica fume, both with and without steel fibers, the best performance was achieved by the WF2 mixture, which can be attributed to the use of ten-pass magnetized water.

5.3 | Flexural Strength Test Results

Using the modulus of rupture equation, the flexural strength of the specimens with and without steel fibers was calculated. The obtained results are presented in *Tables 9* and *10*.

Table 9. Maximum load and flexural strength of specimens with and without steel fibers.

No.	Mix Design	With Fibers		Without Fibers	
		Maximum Flexural Strength	Maximum Load	Maximum Flexural Strength	Maximum Load
1	C1	4.794	15980	3.246	10820
2	C2	5.973	19910	3.861	12870
3	C3	3.786	12620	2.304	7680
4	W1	4.41	14700	2.817	9390
5	W2	4.671	15570	3.915	13050
6	S1	4.362	14540	2.733	9110
7	S2	4.272	14240	3.507	11690
8	WF1	5.583	18610	4.176	13920
9	WF2	5.844	19480	4.866	16220
10	SF1	4.713	15710	3.948	11660
11	SF2	4.986	16620	4.041	13470

Table 10. Percentage difference in flexural strength results of specimens with and without steel fibers.

Mix Design	1	2	3	4	5	6	7	8	9	10	11
Difference (%)	47	54	64	56	19	59	21	33	20	34	23

5.3.1 | Analysis of flexural strength test results

As shown in *Tables 9* and *10*, the maximum load and equivalent flexural strength of the specimens containing steel fibers were higher than those of the corresponding specimens without fibers in all mixtures. This indicates that steel fibers have a positive effect on the flexural performance of concrete. Since concrete has relatively poor tensile strength, reinforcing it with steel fibers improves its behavior under flexural loading and reduces the effects of tensile stresses induced by bending.

However, the difference in maximum load or equivalent flexural strength between fiber-reinforced and non-fiber-reinforced specimens was not the same for all mixtures. For example, in the C1 mixture, which contained natural aggregates and conventional water and served as one of the control mixtures, the maximum load of the fiber-reinforced specimens was approximately 48% higher than that of the specimens without fibers. In the other mixtures, this difference was also greater than 19%.

It can also be observed that the use of recycled aggregates in the control mixture C3 resulted in a significant reduction in the maximum load and equivalent flexural strength of the specimens containing steel fibers. The maximum load of the C3 mixture decreased to 12,620 N (3.786 MPa) for fiber-reinforced specimens and 7,680 N (2.304 MPa) for specimens without fibers.

In contrast, the maximum load for the fiber-reinforced specimens in the C1 control mixture, containing natural aggregates, was 15,980 N (4.794 MPa), while the maximum load for the non-fiber-reinforced specimens in the same mixture was 10,820 N (3.246 MPa).

Furthermore, the use of five-pass magnetized water in the C2 control mixture increased the maximum load to 19,910 N (5.973 MPa) compared with the C1 mixture, which was prepared using conventional water.

By comparing mixtures C3 and W1, which differ only in the type of mixing water, it can be observed that the use of one-pass magnetized water in mixture W1 increased the flexural strength and corresponding maximum load by approximately 48% for fiber-reinforced specimens and 27% for non-fiber-reinforced specimens.

The use of a superplasticizer in mixtures S1 and S2, with dosages adjusted to achieve slump values equivalent to those obtained using magnetized water in mixtures W1 and W2, respectively, improved the flexural strength and maximum load compared with the conventional water mixture (C3). However, these values were still lower than those obtained from the mixtures containing magnetized water (W1 and W2) and did not reach their performance level.

In addition, the incorporation of silica fume in the four mixtures WF1, WF2, SF1, and SF2 resulted in a significant increase in flexural strength and maximum load for both fiber-reinforced and non-fiber-reinforced specimens.

Among these mixtures, WF2, which contained recycled aggregates, ten-pass magnetized water, and 10% silica fume, achieved a flexural strength of 19,480 N (5.844 MPa) for the fiber-reinforced specimens and 16,220 N (4.866 MPa) for the specimens without fibers. These values are significantly higher than those obtained for the C1 control mixture, which contained natural aggregates and conventional water.

It should be noted that the above analyses were based on the maximum load obtained from the load–displacement curves. These analyses alone cannot fully describe the behavior of specimens under flexural loading. The flexural response of specimens with and without steel fibers is fundamentally different, and this difference can be clearly observed from the load–displacement curves.

The effect of steel fibers is also evident from the failure patterns of fiber-reinforced concrete specimens compared with specimens without fibers. Therefore, it is clear that specimens containing steel fibers exhibit significantly different behavior and failure mechanisms compared with non-fiber-reinforced specimens, as illustrated in *Fig. 15*.

a.

b.

Fig. 15. Failure modes of concrete specimens; a. containing steel fibers compared with, and b. specimens without steel fibers.

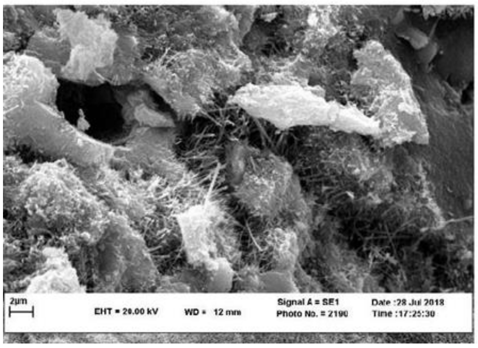
As can be observed from *Fig. 17*, the specimens exhibited two different failure modes. Specimens without steel fibers failed suddenly with a significant release of stored energy. After failure, these specimens were divided into two separate parts that could be easily detached from each other. This failure occurred due to the formation of a deep and continuous crack, and generally, no additional cracks developed within the specimen.

In contrast, specimens containing steel fibers exhibited a different failure mechanism. Although these specimens also developed a deep crack at the moment of failure, they did not split into two separate parts. Furthermore, after reaching the maximum load, the specimens were able to sustain the applied load for a considerably longer period. The failure of fiber-reinforced specimens was not sudden, and the energy dissipation after reaching the peak load occurred gradually.

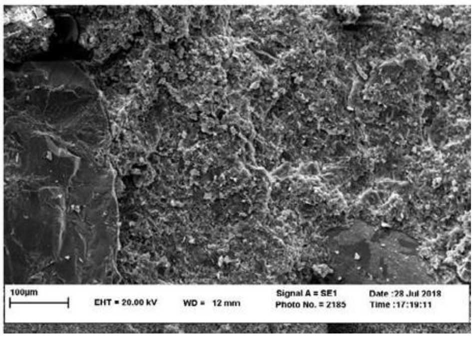
5.4 | Scanning Electron Microscopy Images

These images provide a useful indicator for comparing the quality of concrete specimens in terms of their microstructural characteristics. The specimens selected for imaging were obtained from the samples used in the compressive strength tests. After testing, a small amount of concrete was collected from the damaged region and stored in sealed containers. After collecting all required samples, Scanning Electron Microscopy (SEM) imaging was performed.

It should be noted that SEM imaging was conducted for the three control mixtures (C1, C2, and C3) as well as mixtures W2, S2, and WF2. The reason for selecting these mixtures was to compare the control specimens with concrete mixtures produced using a higher number of magnetization cycles, as well as to evaluate the influence of magnetized water and silica fume on the concrete microstructure.

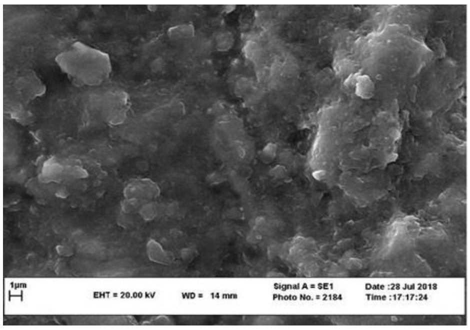


a.

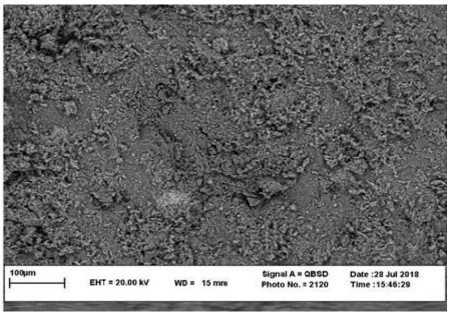


b.

Fig. 16. SEM images of the C1 mixture; a. 10,000 × magnification, and b. 500× magnification.

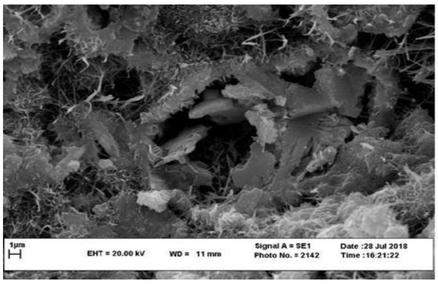


a.

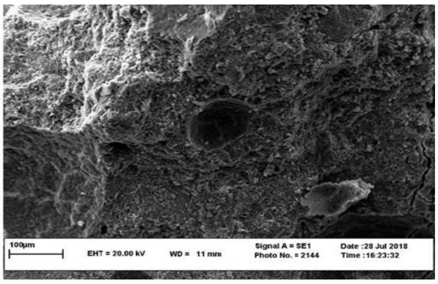


b.

Fig. 17. SEM images of the C2 mixture; a. 10,000× magnification, and b. 500× magnification.

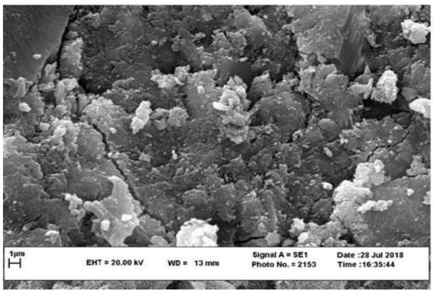


a.

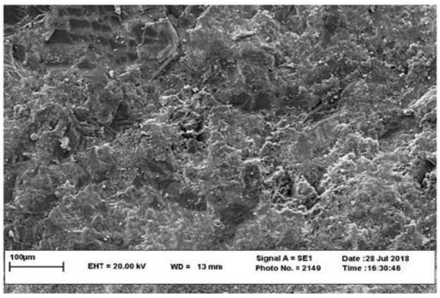


b.

Fig. 18. SEM images of the C3 mixture; a. 10,000× magnification, and b. 500× magnification.

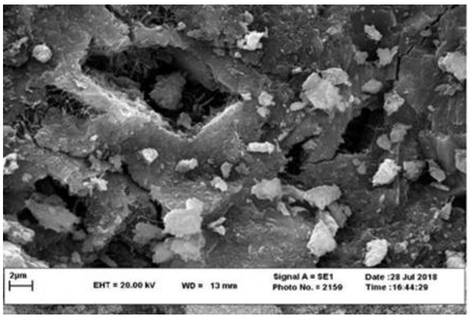


a.

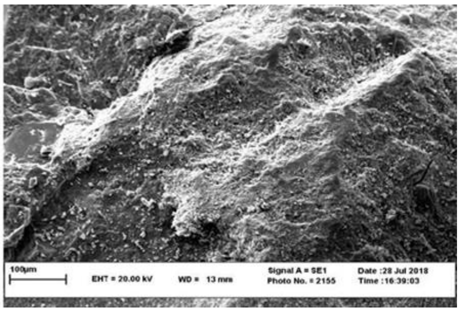


b.

Fig. 19. SEM images of the W2 mixturep; a. 10,000× magnification, and b. 500× magnification.

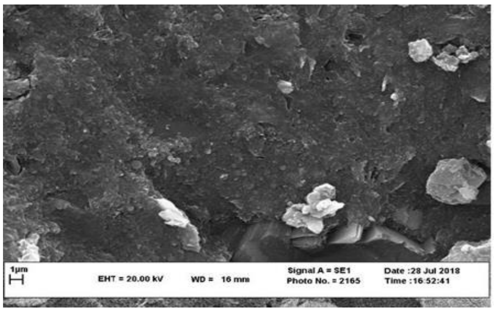


a.

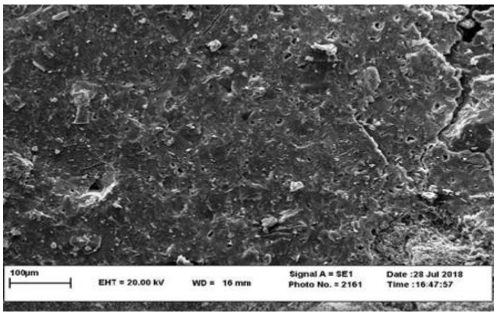


b.

Fig. 20. SEM images of the S2 mixture; a. 10,000× magnification, and b. 500× magnification.



a.



b.

Fig. 21. SEM images of the WF2 mixture; a. 10,000× magnification, and b. 500× magnification.

In all the investigated mixtures, specimens prepared with magnetized water exhibited higher density and a more compact microstructure. *Fig. 16* shows the microstructure of the C1 control mixture. The concrete produced using conventional water exhibited a more porous structure compared with the C2 control mixture shown in *Fig. 17*.

In the C1 mixture, the SEM image at 500× magnification reveals a heterogeneous and irregular structure. Increasing the magnification to 10,000× makes the microstructural defects of this type of concrete more evident. In contrast, the C2 control concrete, which was produced using magnetized water, exhibited a completely homogeneous and uniform structure, as shown in *Figs. 18.a* and *18.b* at magnifications of 500× and 10,000×, respectively.

This improved microstructural quality explains why specimens produced with magnetized water exhibited better performance. The uniform and defect-free structure of these concretes contributed to improved resistance under various mechanical tests.

By examining the C3 control mixture in *Fig. 19*, it can initially be observed that the surface roughness of the concrete produced with recycled aggregates and conventional water is relatively similar to that of the C1 control mixture. However, due to the lower quality of the recycled aggregates, cracks are formed within the structure. At 500× magnification, the specimen exhibits relatively deep cracks, which were not observed in the C1 mixture. Further examination at higher magnification (*Fig. 19.b*) reveals deeper voids within the concrete structure. These micro-scale defects resulted in a significant reduction in concrete strength.

Fig. 20 presents the concrete produced with recycled aggregates and ten-pass magnetized water without silica fume. Examination of this surface indicates that magnetized water has a significant effect on improving the integrity of the concrete surface and the cement paste structure. The W2 mixture exhibited better cement hydration and significantly lower porosity compared with the C3 control mixture. However, the deep cracks observed in the C3 mixture were still present. At 10,000× magnification, these cracks become more apparent. The presence of such cracks can promote crack propagation after loading due to stress concentration at these discontinuities.

In the S2 mixture, produced using conventional water and superplasticizer without silica fume and containing recycled aggregates (*Fig. 20*), the cracks caused by the use of recycled aggregates are clearly visible. However, the dominant feature in this mixture is the presence of numerous small and widely distributed pores throughout the concrete matrix, which become more evident at 10,000× magnification.

For the specimens containing silica fume, as shown in *Fig. 21*, the specimen produced with ten-pass magnetized water does not exhibit large pores. Therefore, the concrete produced with magnetized water has a smoother, more uniform, and more integrated surface structure.

6 | Conclusion

I. The use of recycled aggregates increased the water absorption of the specimens by approximately 47% compared with conventional concrete specimens. It also caused reductions in density and slump of approximately 4% and 50%, respectively, in fiber-reinforced specimens.

II. The use of ten-pass magnetized water compared with one-pass magnetized water increased the slump and reduced water absorption by approximately 40% and 6%, respectively, in fiber-reinforced recycled aggregate concrete specimens without silica fume. For similar mixtures without steel fibers, these values were approximately 33% increase in slump and 2% reduction in water absorption.

III. In fiber-reinforced concrete without silica fume, the use of ten-pass magnetized water increased the compressive, tensile, and flexural strengths by approximately 11%, 5%, and 6%, respectively, compared with one-pass magnetized water. In concrete containing the mineral admixture silica fume, these improvements were approximately 3%, 10%, and 4%, respectively.

IV. The incorporation of silica fume reduced the slump and water absorption by approximately 16% and 8%, respectively, in fiber-reinforced specimens containing ten-pass magnetized water, and by 25% and 10%, respectively, in specimens containing one-pass magnetized water. For specimens without fibers, these reductions were approximately 33% and 9% for ten-pass magnetized water and 25% and 7% for one-pass magnetized water.

Among all investigated mixtures, the WF2 mixture, containing ten-pass magnetized water and 10% silica fume, exhibited the best overall performance. Therefore, magnetized water should not be used alone as a solution for compensating the deficiencies of recycled aggregates; rather, its combination with appropriate supplementary cementitious materials, such as silica fume, provides more effective improvement.

References

[1] Madandoust, R., Mohseni, E., Mousavi, S. Y., & Namnevis, M. (2015). An experimental investigation on the durability of self-compacting mortar containing nano-SiO2, nano-Fe2O3 and nano-CuO. *Construction and building materials*, *86*, 44–50. https://doi.org/10.1016/j.conbuildmat.2015.03.100

[2] de Juan, M. S., & Gutiérrez, P. A. (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and building materials*, *23*(2), 872–877. https://doi.org/10.1016/j.conbuildmat.2008.04.012

[3] Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste management*, *30*(11), 2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

[4] Buck, A. D. (1976). *Recycled concrete as a source of aggregate*. https://erdc-library.erdc.dren.mil/bitstream/11681/11503/1/MP-C-76-2.pdf

[5] Kou, S. C., Poon, C. S., & Etxeberria, M. (2011). Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. *Cement and concrete composites*, *33*(2), 286–291. https://doi.org/10.1016/j.cemconcomp.2010.10.003

[6] Reddy, B. S. K., Ghorpade, V. G., & Rao, H. S. (2013). Effect of magnetic field exposure time on workability and compressive strength of magnetic water concrete. *International journal of advances in*

engineering & technology (IJAET), *4*(3), 120–122. https://paperzz.com/doc/9104672/effect-of-magnetic-field-exposure-time-on-workability-and

[7] Reddy, B. S. K., Ghorpade, V. G., & Rao, H. S. (2014). Influence of magnetic water on strength properties of concrete. *Indian journal of science and technology*, *7*(1), 14–18. https://dx.doi.org/10.17485/ijst/2014/v7i1.7

[8] Manjupriya, T., & Malathy, R. (2016). Experimental investigation on strength and shrinkage properties of concrete mixed with magnetically treated water. *Magnesium*, *290*, 195. https://www.ijeart.com/download_data/IJEART02417.pdf

[9] Patil, S. V, & Pathak, N. J. (2016). The experimental study on compressive strength of concrete using AR glass fibers and partial replacement of cement with GGBS with effect of magnetic water. *International journal of engineering, technology management & applied sciences*, *4*(8), 21-29.

[10] R., E. A., Mohammad, R., & Benjamin, M. (2018). Magnetized water effect on compressive strength and dosage of superplasticizers and water in self-compacting concrete. *Journal of materials in civil engineering*, *30*(3), 4018008. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002174

[11] Matias, D., de Brito, J., Rosa, A., & Pedro, D. (2013). Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers. *Construction and building materials*, *44*, 101–109. https://doi.org/10.1016/j.conbuildmat.2013.03.011

[12] Dutta, B., Mahakavi, P., Gogoi, R., Chithra, R., & Surya, S. (2024). Experimental investigation to study the structural viability of recycled aggregates found in India. In *From waste to wealth* (pp. 1089–1102). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-7552-5_48

[13] Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction and building materials*, *31*, 364–383. https://doi.org/10.1016/j.conbuildmat.2011.12.074

[14] Su, N., Wu, Y. H., & Mar, C. Y. (2000). Effect of magnetic water on the engineering properties of concrete containing granulated blast-furnace slag. *Cement and concrete research*, *30*(4), 599–605. https://doi.org/10.1016/S0008-8846(00)00215-5

[15] Toledo, E. J. L., Ramalho, T. C., & Magriotis, Z. M. (2008). Influence of magnetic field on physical–chemical properties of the liquid water: Insights from experimental and theoretical models. *Journal of molecular structure*, *888*(1), 409–415. https://doi.org/10.1016/j.molstruc.2008.01.010

[16] Karam, H., & Al-Shamali, O. (2013, August). Effect of using magnetized water on concrete properties. *Proceedings of the third international conference on sustainable construction materials and technologies* (pp. 1–12). Japan Concrete Institute. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://waterconditioners.in/reference/6.pdf

[17] Ahmed, S. (2009). Effect of magnetic water on engineering properties of concrete. *Journal of al-rafidain engineering*, *7*(1), 71–82. https://doi.org/10.33899/rengj.2009.38451

[18] Ramezani, A., Modaresi, S., Dashti, P., GivKashi, M. R., Moodi, F., & Ramezanianpour, A. A. (2023). Effects of different types of fibers on fresh and hardened properties of cement and geopolymer-based 3D printed mixtures: A review. *Buildings*, *13*(4), 1–28. https://doi.org/10.3390/buildings13040945