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Improving mechanical properties of recycled fibre-reinforced concrete through the use of magnetic water

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Abstract:
This study investigated the performance of Polyethylene terephthalate (PET), polypropylene, and steel fibres in concrete, utilizing both regular and magnetic water. The primary objectives were to explore the effect of magnetic water on the mechanical properties of fibre-reinforced concrete and to compare the performance of these fibres under identical conditions. Fibres were incorporated at dosages of 1-3 % by volume in concrete prepared with two different water types: regular and magnetic. Tests, including compressive strength, flexural strength, water permeability, and Young's modulus, were conducted on the samples. The results indicated that steel fibres outperformed the other fibre types in terms of overall performance, with the highest compressive strength observed in samples containing 3 % steel fibres. Specifically, among the samples utilizing regular water, the increase in compressive strength compared with the control was approximately 25 %, whereas for samples incorporating magnetic water, the increase was 23 %. In contrast, polypropylene fibres caused a 14 % reduction in compressive strength in both regular and magnetic water samples, whereas PET fibres exhibited similar compressive strength to that of the control sample. Magnetic water demonstrated a positive effect on all concrete properties and improved the microstructure by reducing pore content. Notably, the compressive strengths for samples with magnetic water increased by about 10 % across all fibre types compared with regular water. However, no significant difference in the performance of fibre-reinforced concrete was observed between magnetic and regular water beyond this increase.

Keywords:
magnetic water; concrete; fibres; polypropylene; pet

1 Introduction

Fibre-reinforced concrete employs reinforcing fibres within the concrete mixture to enhance its compressive and tensile strengths, thereby creating a composite material. This type of concrete has been increasingly used in flooring projects in recent years, as it exhibits improved flexural and tensile strengths and reduced cracking. Fibres from different materials have been produced and used in concrete. Each of these fibres has unique characteristics that change the properties of concrete to different degrees [1].

Fibres serve as reinforcement elements to enhance the tensile strength of concrete. Their presence also facilitates crack control and enhances the ductile properties of concrete [2-4]. The strengthening mechanism involves the transfer of stress from the matrix to the fibres via either shear or cohesive bonding, which is particularly effective when the fibre surface is ribbed. Therefore, if the concrete matrix is not cracked, the tensile stress is divided between the fibres and matrix. After cracking, all the stresses are transferred to the fibres [5; 6].

Owing to the daily increase in the use of fibres in concrete, this study examined the effects of PET, polypropylene, and steel fibres. Notably, these fibres are sourced as recycled materials, and their production processes involve several stages. The PET fibres were produced by recycling polyethylene terephthalate bottles that were processed via a mechanical shredding process that was followed by fibre extrusion. In contrast, steel fibres are manufactured by cutting steel wires into specific lengths, and the production process typically involves the use of high-quality steel to ensure durability and strength. Incorporating these recycled materials into concrete aligns with the principles of sustainable development by minimising raw material consumption and promoting material recycling [7-9].

Given the considerably high worldwide production of PET, its use in concrete appears promising. Ramadevi et al. documented that incorporating 2 % recycled PET into concrete resulted in an elevated tensile strength compared with conventional concrete [10]. Ghasemi et al. demonstrated that the addition of 0,5 and 1,0 % PET fibres led to 4,0 and 15,0 % increases in the tensile strength of concrete, respectively, compared with conventional concrete [11]. Research indicates that in regular concrete and self-compacting concrete (SCC), reinforced with 60 mm-long polypropylene fibres, an increased fibre content contributes to a reduction in the compressive strength and Young’s modulus while concurrently enhancing the tensile strength [12; 13]. Changing the fibre rate can change the mechanism, rheology, and precise cracking behaviour [14]. This behaviour has been confirmed in several studies [15; 16]. Furthermore, increasing the amount of steel fibres by up to 3,5 % increases the flexural strength. Any further increase in the fibre content leads to a reduction in the flexural strength [17; 18]. Another study on the properties of concrete with high reinforced strength with alkaline polypropylene fibres and alcohol polyvinyl fibres showed a noticeable reduction in the compressive strength and Young’s modulus of concrete [19].

However, water also significantly affects the properties of concrete. On a macro scale, water influences the amount of porosity, and on a micro scale, water influences the formation of hydration products and their properties [20; 7]. Magnetic water has distinct properties from ordinary water because of its exposure to a magnetic field. The process of magnetising water is simple and does not require additional energy. Water is magnetised by passing it through a constant magnet that induces lasting changes in its molecular structure. Typically, water molecules are interconnected by hydrogen bonds, which leads to the formation of clusters. However, when water flows through a magnetic field, the molecular clusters break up, and the sizes of the clusters decrease, as does the number of molecular cells, resulting in the increased reactivity of water [21; 22]. Magnetic water also has a low surface tension, which improves its interaction with materials such as cement. The increased reactivity and surface tension reduction are the reasons why magnetic water has been widely used in various industries, including construction, to improve concrete properties.

Several studies have explored the impact of magnetic water on the mechanical properties of concrete, such as the compressive strength, flexural strength, and permeability. For instance, a study highlighted that magnetic water can enhance the hydration efficiency and significantly improve the mechanical performance of concrete [23].

Upon adding water to cement, a hydration process is initiated at the surface of the cement particles, thus forming a thin layer of hydration particles around them. However, this layer hinders the hydration of the remaining cement particles [24], which thereby hinders the improvement of the concrete properties. Magnetising water prevents the agglomeration of cement particles and leads to the better penetration of water into the cement particles, which leads to the better hydration of cement and improves the concrete properties [25-29]. The principal benefit of employing magnetic water is its ability to augment the strength properties of concrete while simultaneously decreasing the water-to-cement ratio. The utilisation of magnetic water leads to notable enhancements in compressive and tensile strengths, with reported increases of up to 60 %. Additionally, the incorporation of magnetic water has a positive impact on the workability of concrete, and thereby contributes to improved workability to a certain extent [25]. Recent research has also suggested the potential of combining magnetic water with fibres, thus offering enhanced performance over conventional fibre-reinforced concrete [30].

Despite the benefits associated with both magnetic water and fibre concrete, a thorough investigation on the utilisation of magnetic water in fibre concrete is lacking. Therefore, the primary objective of this study is to assess the impact of magnetic water on concrete blends that integrate polypropylene, steel, and PET fibres.

2 Methodology

2.1 Materials

The cement employed in this study adhered to the ASTM C150 standard, specifically Type 2, and was sourced from the Sabzevar Jovein Cement Factory. The properties of the cement used in this study are listed in Table 1. The sand used in this study came from a crushed river provided by local sources, all of which met ASTM standards.

This study incorporated three distinct fibre types: steel, polypropylene, and PET. The steel fibre featured dual hooks at its extremities, measuring 36 mm in length and 0,8 mm in diameter. Each possessed a specific weight of 7850 kg/cm and culminated at a 40° angle at the end of each hook. In contrast, the polypropylene fibres measured 6 mm in length and had a diameter of 0,0021 mm and weight of 0,92 kg/cm. Finally, the PET fibre was 6 mm long, 0,0021 mm in diameter, and weighed 1,45 g/cm^3.

Table 1. Cement properties

Chemical components (%)		**Physical properties**	
CaO	63,68	Autoclave expansion (%)	0,12
SiO_2	21,02	Specific surface area (cm^2/gr)	3314,00
Fe_2O_3	3,81	Setting time, Initial (min)	92,00
Al_2O_3	5,04	Setting time, Final (min)	254,00
MgO	2,88	Specific gravity (g/cm^3)	3,16
Na_2O	0,43	Free CaO (%)	1,08
K_2O	0,51		
SO_3	2,49		
LOI	1,97		

For this study, the water was sourced from the potable water supply of Neyshabur County, which was used first as normal water and again as magnetic water. To produce magnetic concrete, the potable water in the lab was magnetised by passing it through Correct-Aqua AC machinery made in Germany with a flow of 2,26 L/min and a field intensity of 1 T (Figure 1). Water was circulated within the machinery for various durations, resulting in diverse concrete samples. Based on this experiment, the optimal water circulation duration was determined to be 40 min. Beyond this timeframe, the circulation of water no longer affected the properties of the concrete.

Figure 1. Correct-Aqua AC machinery

2.2 Methods

In this study, the mixture was augmented with steel, polypropylene, and PET fibres, each constituting 1,0; 2,0; and 3,0 % of the total cement weight. Moreover, two sets of mix designs were formulated. The first utilised conventional water, and the second incorporated magnetic water. Magnetic water was created by passing ordinary water through a magnetic field generated using a permanent magnet. This treatment was intended to alter the molecular structure of water, increase its reactivity, and enhance the hydration of concrete. Thus, 18 mixed designs with fibres and two control plans were prepared. Table 2 lists the proportions in each group.

For each mixture, 24 samples were prepared, including six cylindrical (30 × 15 cm), nine cubic (15 × 15 × 15 cm), and nine prism cubic (10 × 10 × 5 cm) samples. Three cylindrical specimens were employed to ascertain the Young's modulus after 28 d, and another set of three cylinders was employed to examine the porosity at the same age. Additionally, of the nine cubic samples, three were allocated for evaluating the compressive strength at 7 d, another three for assessing the compressive strength at 28 d, and the remaining three for measuring the compressive strength at 90 d. Additionally, nine prism specimens were used to estimate the flexural strength at 7, 28, and 90 d of age. A slump test was also performed on all mix designs.

A mixer with a capacity of 120 liters was used to prepare the samples in the laboratory. First, the aggregates were mixed with water in a mixer, and then cement and fibres were gradually added to the mixture. Finally, the remaining water was introduced. Subsequently, the prepared concrete was carefully poured into moulds, and this was followed by execution of the necessary vibration and compression procedures. In the next stage, the specimens were stored in a saturated limestone water pool in accordance with the ASTM C 192-81 standard and remained under these conditions until the day of the experiment. After preparing the samples, their compressive strength was determined based on the BS 1881 standard, and the flexural strength of the prismatic models was determined based on the ASTM C293 standard. Finally, the ASTM C469 standard was used to assess the Young's modulus of concrete, and the BS EN 12390-8 standard was used to evaluate the permeability of the samples.

One limitation of the current study is the relatively small sample size and the potential variation in fibre quality owing to sourcing from different suppliers, which may have influenced the results. Hence, further studies with larger sample sizes and consistent fibre qualities are recommended.

Table 2. Concrete mixture proportions

Mix. name	Constituents (kg/m³)							
	Steel fibers	PP fibers	Pet fibers	Cement	Water	Magnetic water	Gravel	Sand
C	--	--	--	350	182	--	857	859
PET-1	--	--	3,5	350	182	--	857	859
PET-2	--	--	7	350	182	--	857	859
PET-3	--	--	10,5	350	182	--	857	859
ST-1	3,5	--	--	350	182	--	857	859
ST-2	7,0	--	--	350	182	--	857	859
ST-3	10,5	--	--	350	182	--	857	859
PP-1	--	3,5	--	350	182	--	857	859
PP-2	--	7,0	--	350	182	--	857	859
PP-3	--	10,5	--	350	182	--	857	859
CM	--	--	--	350	--	182	857	859
PET-M-1	--	--	3,5	350	--	182	857	859
PET-M-2	--	--	7	350	--	182	857	859
PET-M-3	--	--	10,5	350	--	182	857	859
ST-M-1	3,5	--	--	350	--	182	857	859
ST-M-2	7,0	--	--	350	--	182	857	859
ST-W-3	10,5	--	--	350	--	182	857	859
PP-W-1	--	3,5	--	350	--	182	857	859
PP-W-2	--	7,0	--	350	--	182	857	859
PP-W-3	--	10,5	--	350	--	182	857	859

3 Results

3.1 Slump

After producing the samples and testing their consistencies, a slump test was performed. Table 3 presents the relevant results of this study. The fibre mitigates the consistency of the concrete, as has been confirmed in previous studies [2]. Moreover, polypropylene fibre reduces concrete consistency owing to its high water absorption. This study has certain limitations. The use of magnetic water improves the surface of concrete and compensates for the reduction in consistency in concrete containing fibres. Magnetic water participates more actively in the hydration process, primarily owing to changes in the molecular arrangement, and can increase the concrete surface area [29]. Hence, the fibre reduced the performance of magnetic water in improving the consistency of concrete to an extent.

Table 3. Slump test

Mix. name	Slump (cm)	Mix. name	Slump (cm)
C	5,0	CM	7,0
PET-1	3,5	PET-M-1	4,0
PET-2	2,0	PET-M-2	2,5
PET-3	1,5	PET-M-3	2,0
ST-1	4,0	ST-M-1	5,0
ST-2	3,5	ST-M-2	4,0
ST-3	3,0	ST-W-3	3,5
PP-1	3,0	PP-W-1	4,0
PP-2	2,0	PP-W-2	2,5
PP-3	1,0	PP-W-3	1,0

3.2 Compressive strength

The compressive strength analysis encompassed all samples containing the three fibre types, utilising both normal and magnetic water. Figures 2 and 3 illustrate the compressive strength results for the models using conventional and magnetic water, respectively. Throughout all stages of aging, for both water types, the concrete specimens with steel fibres consistently demonstrated superior compressive strength compared with the control concrete. In particular, this specific fibre type displays an advantageous compressive strength. Among the samples, the highest compressive strength was recorded for the concrete containing 3 % steel fibres.

Among the samples utilising regular water, the most substantial increase in compressive strength compared with that of the control sample was approximately 25 %. For the samples incorporating magnetic water, the corresponding enhancement value was approximately 23 % compared with the control samples made with regular water.

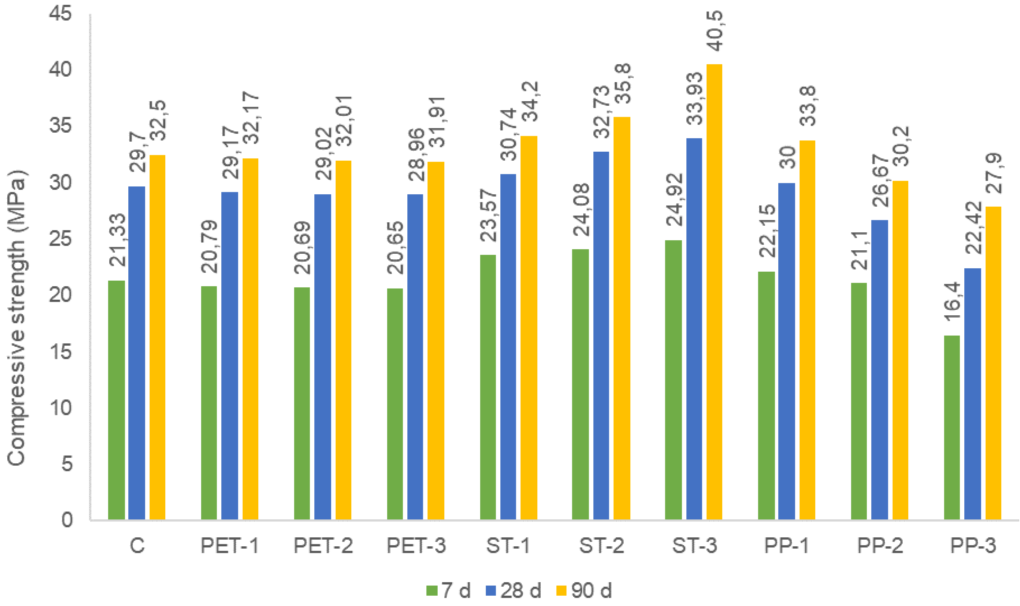


Figure 2. Results of compressive strength tests on specimens with normal water

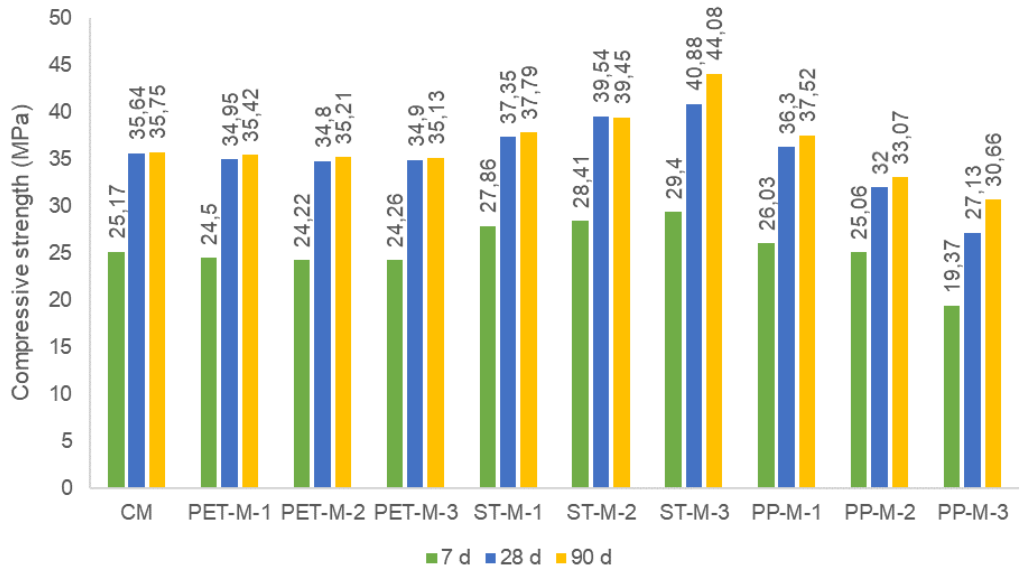


Figure 3. Results of compressive strength tests on specimens with magnetic water

The greatest decrease in strength was observed for the samples containing polypropylene fibres. This reduction was approximately 14 % in both the normal and magnetic water samples, accounting for 3 % of the fibre. In addition, the strengths of the PET samples were similar to that of the control sample.
Comparing the samples containing magnetic water and normal water, an increase in compressive strength was observed in all samples containing magnetic water. This increase was approximately 10 % compared with the control sample. This percentage of growth was also observed in all samples containing fibres (almost 10 %). Interestingly, when magnetic water was used, the compressive strengths of the samples at 28 and 90 d of age exhibited a close resemblance.
This phenomenon is attributable to the interaction between water and cement and the implementation of the hydration process at lower ages. More specifically, the increase rate of strength with magnetic water at 28 d exceeded 20 %. However, the age of concrete increased, and part of this reduction was compensated for in the concrete with normal water via the hydration process. Hence, magnetic water generally contributes to increased compressive strength and expedites the strength development of concrete at an earlier stage. However, this effect was not observed at 7 d, and the best performance was observed at 28 d. This improvement in compressive strength using magnetic water has been reported in the literature [25-29; 31; 32]. The notable enhancement in the compressive strength of concrete achieved using magnetic water is attributable to its larger specific surface area compared with regular water. When water interacts with a magnetic field, it leads to a reduction in the size of the water clusters and number of grouped molecules. This outcome is attributable to the more efficient interaction between water and cement, which enhances the hydration process and refines the microstructure of the cement paste [26]. The impact of magnetic water on the compressive strength of samples containing fibres did not exhibit a significant difference compared with that of the control sample, and no significant positive or negative effect was observed in the fibre concrete when using magnetic water.

3.3 Flexural strength

The flexural strength results for samples containing regular and magnetic water are presented in Figures 4 and 5, respectively.

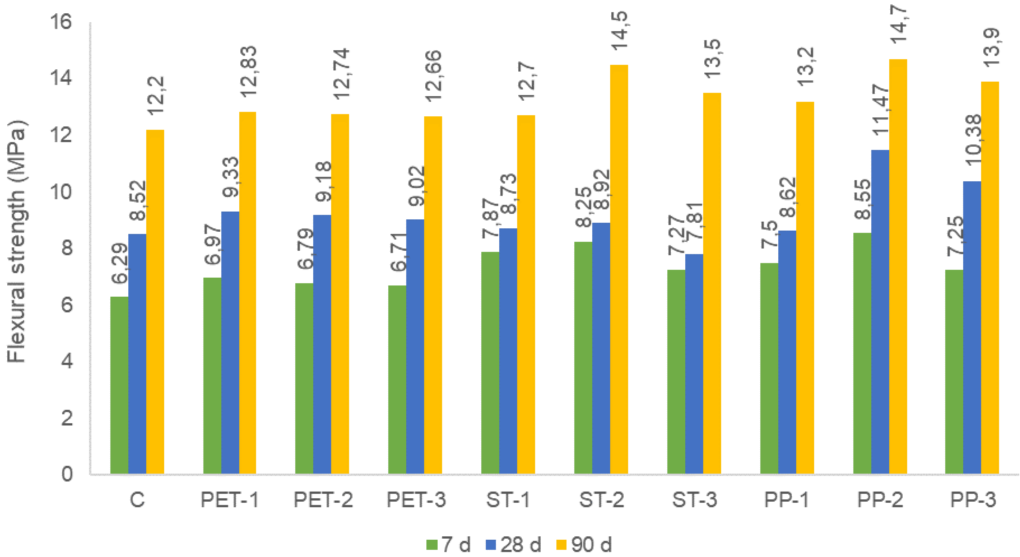


Figure 4. Results of flexural strength tests on specimens with normal water

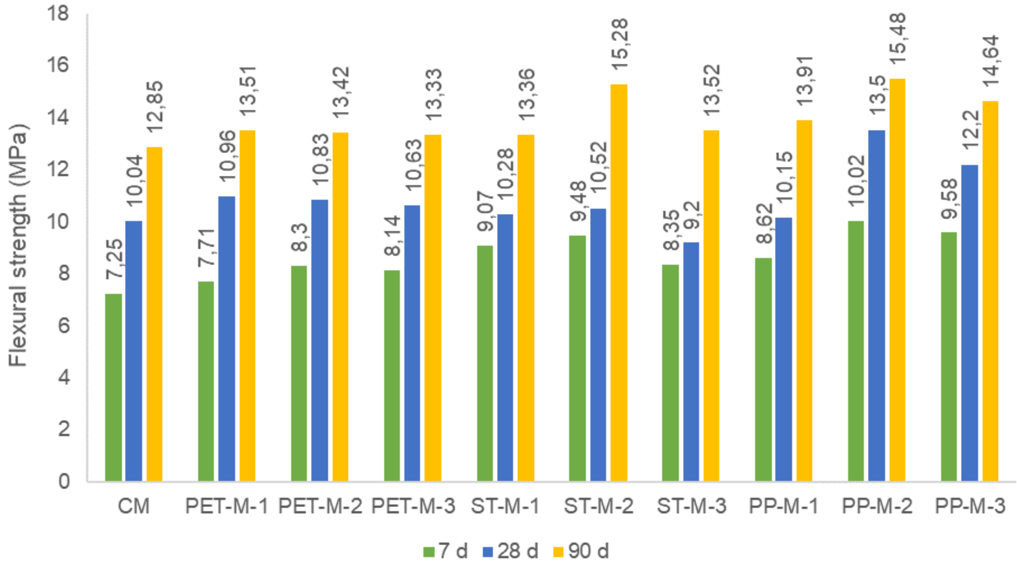


Figure 5. Results of flexural strength tests on specimens with magnetic water

The fibres exhibited good flexural strength. In general, fibres improve flexural strength. The highest strength was observed in the samples containing 2 % polypropylene fibres, which caused a 20 % improvement in the flexural strength. Additionally, the use of 2 % steel fibres yielded similar results. Given these results, all threads at different rates improved the flexural strength of the concrete. The increasing effect of magnetic water on the flexural strength of the samples was approximately 5 % compared with that of the corresponding samples made with regular water, which was lower than that for the compressive strength. However, the rate of improvement was significant. The exact rate of increase was also confirmed in the literature [28]. Similar to the observed increase in compressive strength, this increase is primarily attributable to the enhancement of the hydration process, which is a consequence of the use of magnetic water.

3.4 Young's modulus

The modulus of elasticity was also considered. Figures 6 and 7 show the findings regarding the modulus of elasticity at 28 d for samples containing regular and magnetic water, respectively.

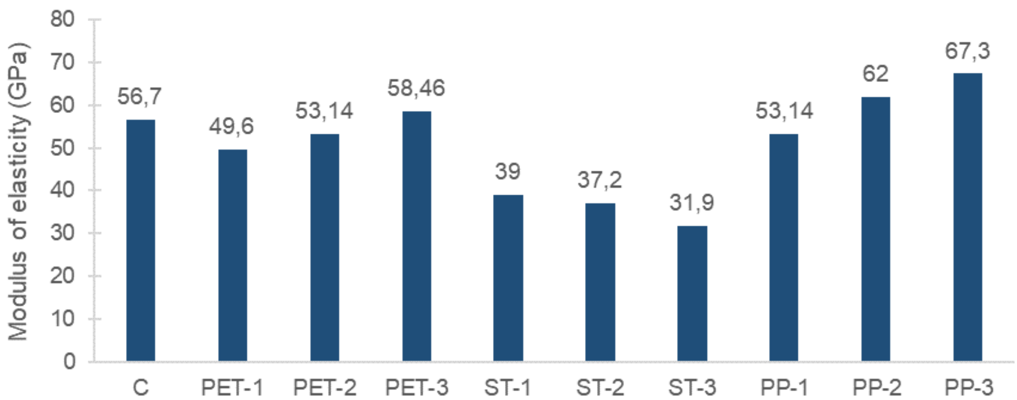


Figure 6. Results of Young's modulus tests on specimens with normal water

The highest increase in the Young's modulus was observed in samples with 3 % polypropylene fibre, which resulted in an improvement of approximately 15 %. The 1 and 2 % replacement

ratios of this fibre did not significantly affect the Young's modulus. The superior performance of polypropylene fibres in enhancing the Young's modulus is attributable to their abilities to control microcracking and distribute stress more effectively within the cementitious matrix.
Conversely, the steel fibres exhibited the weakest performance, as they led to a slight reduction in the Young's modulus for all samples. These results can be explained by the higher ductility and lower dispersion, which may have resulted in localised stress concentrations and the decreased stiffness of the composite material.

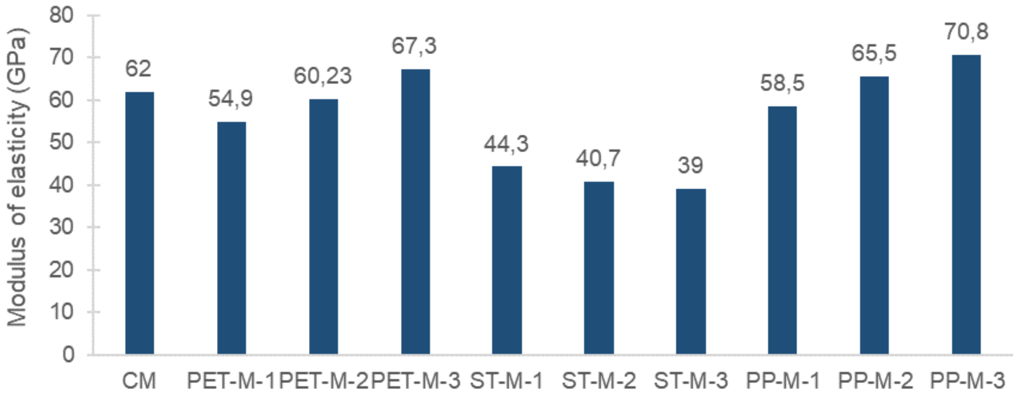


Figure 7. Results of Young's modulus tests on specimens with magnetic water

The inclusion of PET fibres led to a modest 3 % enhancement in the Young's modulus, which is likely attributable to its reinforcing effect in restricting microcracks.
Additionally, magnetic water contributed to a 10 % increase in the Young's modulus, likely owing to its abilities to improve hydration and refine the microstructure thereby leading to a denser and stiffer cementitious matrix.

3.5 Permeability

A permeability test was performed on all the samples at 28 d (Figure 8). Figures 9 and 10 present the results obtained for normal and magnetic water, respectively.

Figure 8. Measuring the porosity depth

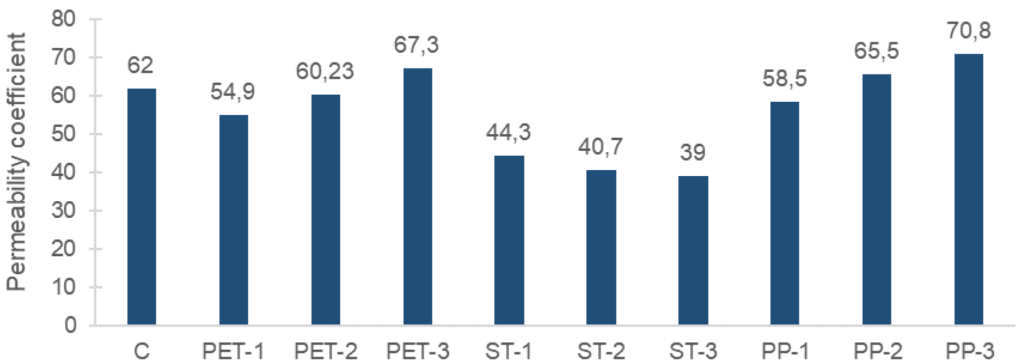


Figure 9. Results of permeability tests on specimens with normal water

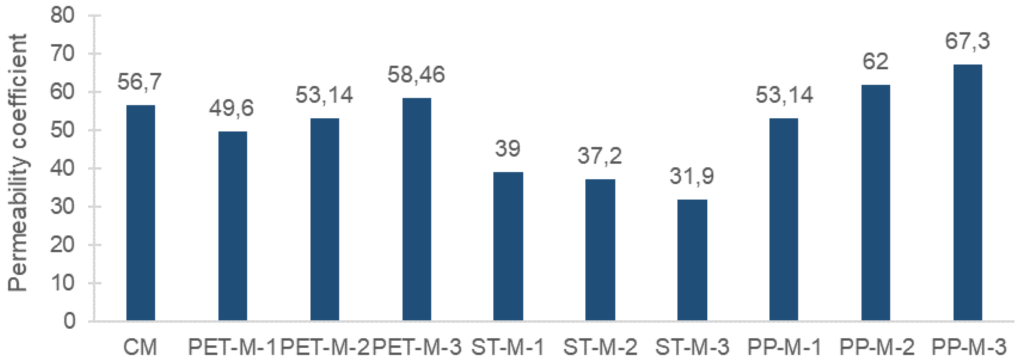


Figure 10. Results of permeability tests on specimens with magnetic water

Steel fibres demonstrated a strong ability to reduce the permeability of concrete. Specifically, using 3 % steel fibres led to an approximately 40 % reduction in porosity depth, whereas using 1 % steel fibres reduced the porosity depth by approximately 26 %. The superior performance of steel fibres in lowering permeability is attributable to their abilities to enhance crack bridging and densify the microstructure, which effectively blocks the pathways for fluid ingress.

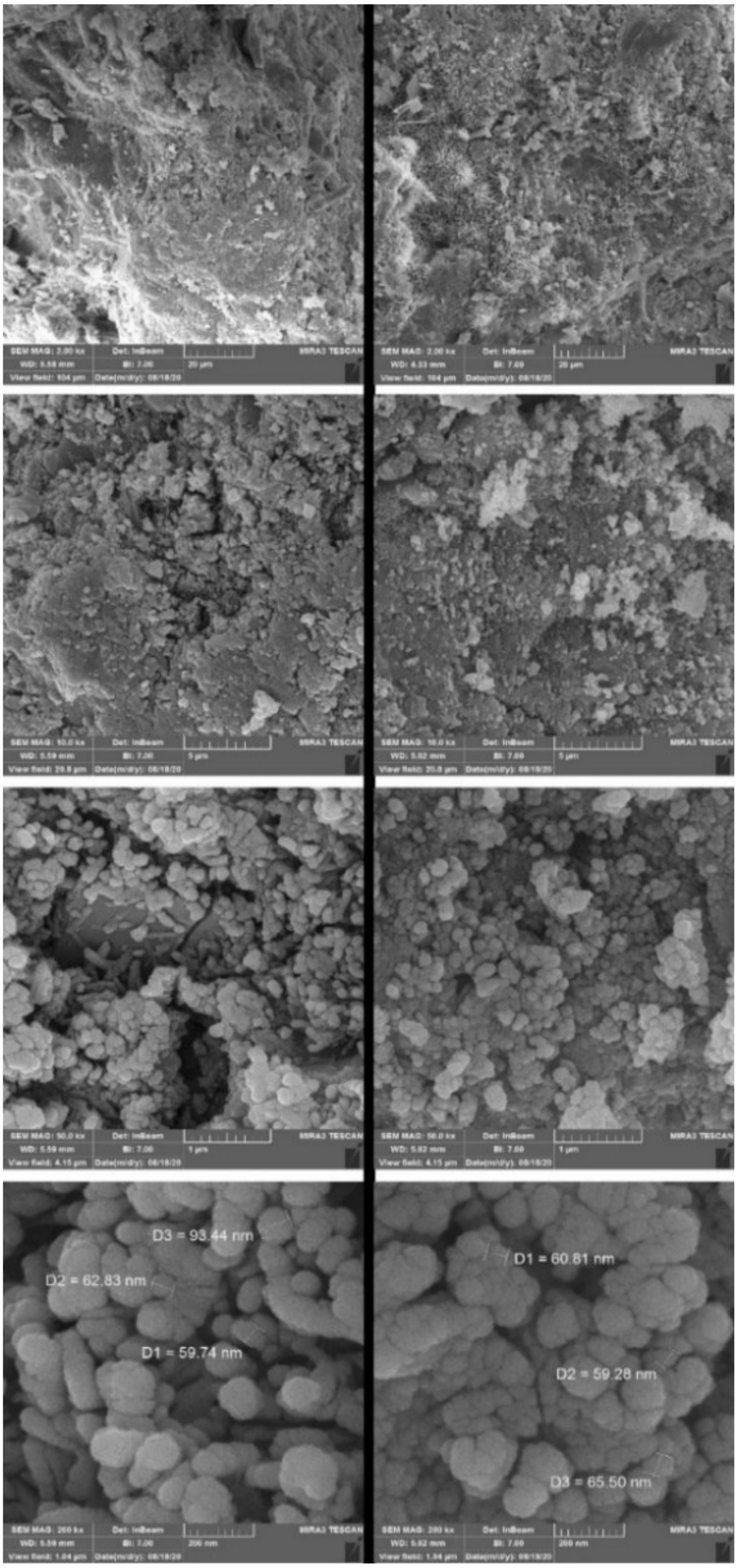
In contrast, the polypropylene fibres exhibited a weaker effect on permeability. Although 1 % polypropylene fibre slightly reduced the porosity depth, higher dosages (2 and 3 %) increased the permeability. This increase may be attributable to fibre agglomeration and the creation of additional voids, which can facilitate fluid transport.

Similarly, the PET fibres had a minimal impact on permeability. The porosity depth of the 1% PET fibre decreased by approximately 12 %, the 2 % PET fibre caused an insignificant reduction, and the 3 % PET fibre increased the porosity by 3 %. These results suggest that at higher dosages, the PET fibres may have induced void formation rather than improved matrix densification.

These observations indicate that the fibre type and content significantly influence both the Young's modulus and permeability, as they affect the microstructure, crack propagation, and overall matrix densification in different ways.

3.6 Microstructure

Figure 11 shows the microstructure of the concrete. Column A was related to concrete with normal water, and column B was connected to concrete with magnetic water. These images were prepared at different magnifications (1000 to 100000 times) and show the difference in the cement paste structure of the two kinds of concrete. The observations show that the microstructure of concrete subjected to magnetic water exhibited greater density and fewer pores than that of concrete subjected to regular water. At higher magnifications, denser crystals were clearly visible, and this issue has been confirmed in the literature [25; 30; 32]. The denser structure with fewer pores was attributable to the hydration process of the cement, which led to the production of more hydration products. Hence, the higher hydration of cement is attributable to the better interaction between the magnetic water and cement particles. The improved mechanical and durability properties of the samples containing magnetic water can be explained well by the denser and less defective microstructure and fewer voids.



a) b)

Figure 11. Concrete microstructure: a) normal water concrete; b) magnetic water concrete

3.7 Sustainability in concrete production and future research

Given the increasing demand for sustainable building materials, the use of magnetic water and recycled fibres, such as polypropylene and PET, offers significant potential to enhance the sustainability of concrete production in practical applications. Magnetic water not only boosts the hydration process by improving the bonding between cement particles but also promotes more uniform curing, which can be crucial for large-scale projects in which consistency and curing speed are key factors, which could result in energy savings during the curing process, especially in large concrete structures, such as bridges, high-rise buildings, and pavements, which typically require significant energy and time for curing.

Furthermore, the integration of recycled fibres, such as PET and polypropylene, provides considerable environmental benefits. By incorporating these fibres, which would otherwise be waste products, the concrete industry can reduce its dependence on virgin materials and thereby mitigate the environmental impacts of raw material extraction and processing. In real-world construction, these fibres can enhance the tensile strength and durability of concrete and thereby increase its resistance to cracking and wear in high-stress environments, such as highways, industrial floors, and other infrastructures that are subjected to continuous mechanical loading.

This approach aligns with the principles of a circular economy, in which materials are continually reused and recycled to minimise the overall carbon footprint of concrete production. Recycled fibres can also be locally sourced from waste materials, which further reduces transportation-related emissions. The improved properties of concrete containing magnetic water and recycled fibres, such as enhanced mechanical performance and increased durability, make it a viable option for demanding applications, such as concrete used in seismic zones, heavy-duty structures, and long-lasting infrastructure.

Finally, the use of magnetic water and recycled fibres not only fosters an eco-friendly production process but also provides practical advantages by enhancing the performance and longevity of structures, ultimately reducing maintenance costs over time. This method illustrates how sustainable practices in concrete production can be seamlessly integrated into the construction industry without compromising the structural integrity or performance.

Future research should focus on exploring the long-term durability of concrete with magnetic water and fibres, especially considering factors such as corrosion resistance and environmental sustainability. Further studies could also investigate the synergistic effects of different types of fibres and their combinations with magnetic water on the concrete properties under various environmental conditions. Additionally, simulations at multiple scales can be performed to better understand the behaviour and performance of fibre-reinforced concrete with magnetic water under different environmental stresses.

Future studies should also include simulation models to better understand the long-term behaviour and durability of concrete containing magnetic water and recycled fibres [33] to facilitate the optimisation of mix designs and prediction of how these materials perform under different environmental conditions, which would ultimately improve the overall sustainability of concrete production.

4 Conclusions

In this study, the combined influence of polypropylene, polyethylene terephthalate (PET), and steel fibres in conjunction with magnetic water on the mechanical properties and porosity of concrete was investigated. The research outcomes revealed the following:

- The utilisation of magnetic water led to an enhancement in all concrete properties. This behaviour is similar to that of conventional fibre concrete.
- For the samples containing steel, a higher compressive strength was obtained, and with an increase in the quantity of fibres, there was a corresponding increase in compressive strength.

- Both steel fibres and polypropylene have demonstrated favourable performance in enhancing the flexural strength of concrete. Notably, a significant increase in flexural strength was observed with a 2 % replacement of these fibres.
- Concrete samples containing PET and polypropylene fibres exhibited an increase in the modulus of elasticity. Conversely, samples containing steel fibres exhibited a decrease in the modulus of elasticity.
- The permeability of the samples containing steel fibres was lower than those of the other samples; however, the permeability of the samples containing polypropylene fibres increased.
- Based on these findings, it is recommended to use polypropylene fibres with a 2-3 % replacement ratio for concrete made with magnetic water, as they have demonstrated the best performance in improving mechanical properties, such as the compressive strength, flexural strength, and modulus of elasticity.

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