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REVIEW

A bibliometric analysis and comprehensive review of magnetized water effects on concrete properties

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Abstract

This study is a critical review to assess the feasibility of using magnetic water to boost the overall performance of concrete. This is specifically conducted by evaluating the improvements of mechanical properties (split tensile strength, compressive strength, and flexural strength), cement particle water absorption, and cement hydration of concrete as a result of adding magnetic water if compared to concrete made with regular tap water. The benefits and associated challenges of utilising magnetic water in concrete are thoroughly discussed based on the most recent experimental and numerical studies published in the open literature between 2019 and 2023. According to the findings, the tensile strength, compressive strength, flexural strength, and electrical conductivity increase by 6.1%, 24.4%, 3.9%, and 0.5%, respectively, in concretes created with MW compared to regular tap water. Also, the magnetic field intensity of 1.3 Tesla yields the greatest improvement in the slump by 5–13 mm. However, the magnetic water shows the highest sorptivity at a magnetic field intensity of 0.9 Tesla. Also, using magnetic water makes concrete block pavers less absorbent of water and more resistant to assault by sulfuric acid. This review would encourage future research and widespread use of magnetic water in concrete production.

Keywords Compressive strength · Magnetized water (MW) · Magnetic field intensity (MFI) · Flexural strengths · Surface tension

Abbreviations

CBA	Cement-based adhesive
GGBS	Ground Granulated Blast-furnace Slag
GWD	Granite waste dust
LWCs	Lightweight concretes
MFI	Magnetic field intensity
MW	Magnetic water
MWD	Marble waste dust
NFA	Natural fine aggregates
PRC	Partial replacement of cement
RTW	Regular tap water
SCC	Self-compacting concrete

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SEM	Scanning electron microscopy
SFRC	Steel fibre reinforced concrete
T or Tesla	Magnetic flux density or magnetic B-field strength (weber/m2)
TDS	Total dissolved solids
UCFA	Untreated coal fine aggregate
VA	Volcanic ash
W/B	Water-to-binding agent ratio
W/C	Glutamate-rich protein
AMA1	Water-to-cement ratio

Introduction

Due to its tremendous strength and resilience under stress, strengthened concrete is one of the most commonly used building materials in existence today. Tensile stresses must be absorbed by the tension side of the concrete section since the tensile strength of concrete is only about 10% as strong as its compressive strength. Tensile forces are transmitted from the concrete to the steel through the steel-concrete connection. It is the bond strength between the concrete and steel that determines the tensile strength of the section (Saleh et al., 2018; Alkhazraji et al., 2019). To achieve the desired strength, water is essential in the concrete mix for both the hydration of cement and preserving processes. Most of the time, people would use regular tap water (RTW) to mix concrete since it is readily available and clean. The crucial problem of optimizing water utilization in concrete manufacturing was highlighted by the scarcity of available RTW. Workability, compressive strength, splitting strength, and water adsorption are only some of the mechanical characteristics of concrete that are directly influenced by the chemical-physical structure of water (Jain et al., 2017).

The magnetization of water and magnetized water (MW) can be made by passing water through a magnetic field at a consistent speed. By enhancing the hydration of negative ions, magnetization intensifies the undesirable effect on the structure of the water crystal. The hydration process starts on the surface of cement when water and cement are mixed (Faris et al., 2014). This prevents the progress of the mechanical strength of concrete because the cement particles are prevented from further hydration by a thin layer of hydration products that accumulate on them (Harsha et al., 2018). On the contrary, employing MW makes it easier for water molecules to enter cement particles, which promotes a thorough hydration process, which increases the mechanical strength of concrete (Hasaan et al., 2018). Together, this limitation and the worldwide scarcity of potable water have brought attention to the critical problem of water efficiency in concrete buildings. Using MW to reduce the quantity of water needed to make concrete has shown encouraging results (Ghorbani et al., 2018; Srinidhi et al., 2019). In other words, because it generates ecologically friendly concrete by reducing cement content and minimising contamination, the MW technique has received current scientific interest. Additionally, the problem of high sulphate concentrations in the sand might be overcome (Al-Hubboubi & Abbas, 2018).

There is a substantial amount of research on the effects of MW on concrete properties (Su et al., 2000; Su & Wu, 2003; Afshin et al., 2010; Ahmed, 2017; Wei et al., 2017; Gholhaki et al., 2018; Ghorbani et al., 2018). It is widely recognized that utilizing MW when mixing concrete can increase both the malleability and strength of the finished product. Su et al. (2000) and Su and Wu (2003) looked into the effects of MW on mortar and concrete that contained fly ash or powdered granulated blast furnace slag. The researchers indicated that using MW in place of Regular Tap Water (RTW) could improve the fluidity of fresh concrete. While this was happening, recommendations of 0.8 to 1.2 Tesla (symbol: T) for the ideal magnetic field intensity (MFI) were made, and enhancements of 10–23% in compressive strength were also achievable.

Despite the importance of understanding the mechanisms of improvement of mechanical properties, cement particle water absorption, and cement hydration of concrete via the utilization of MW, it is rare to find a comprehensive review to evaluate the evolution of this technology and demonstrate the mast associated challenges towards its optimum applications. Up to the authors' knowledge, the research team of Raut et al. (2022) only reviewed the progress of MW technology in the industry of concrete. The review briefly focused on demonstrating the advantages of using MW on properties of concrete while revising the most recent published studies between 2018 and 2012. Accordingly, this study attempts to fill this gap in the open literature by conducting a thorough review to appraise the numerical and experimental studies of using MW in the enhancement of concrete performance.

The influence of employing MW to improve concrete qualities is discussed in detail in the current review, along with a number of technical, research, and development approaches. Because of the many obstacles that still need to be researched into the utilization of MW in strengthening concrete qualities, the results of the recent review may serve as a road map for future investigations. This is due to the fact that they will aid researchers in comprehending the vast array of unanswered problems.

Conceptual facts of the magnetization process of water

Liquid H_2O that has been purposefully exposed to a magnetic field with the goal of changing its molecular structure is referred to as "magnetic water (MW)". MW is water that has been exposed to a strong magnetic field. The magnetic fields are created by the motion of charged particles, as demonstrated in Fig. 1. When electrons pass across a wire, for instance, a magnetic field is produced. The electromagnet is a straightforward device made up of a large number of wire coils coiled around a solid iron core. There will not be a magnetic field if there is no electricity flowing through the wire coils (Jouzdani & Reisi, 2020).

The physical characteristics of water are altered when it is subjected to a magnetic field. Understanding the underlying distinction between ordinary and MW depends on hydrogen bonding. Hydrogen bonds cause the water molecules in ordinary water to group. Water molecules are drawn to one another and gather together to form clusters. These hydrogen bonds, however, are disrupted and these clusters are smaller when exposed to a magnetic field, which in turn boosts the activity of water molecules.

Studies related to the use of MW in concrete

This review has split the published studies on using MW in concrete production into two main categories as follows;

- ***Concrete properties and performance***: This category can include studies that investigate the impacts of MW on concrete properties such as compressive strength, workability, long-term durability, slump, and so on.
- ***Microstructure, mechanisms and interactions***: This category discusses the studies that delve into the microscopic analysis of cement paste, mortar, and concrete to understand changes in microstructure resulting from MW. Furthermore, the studies that related to underlying mechanisms by which MW interacts with water molecules, influences cement hydration, and potentially affects the microstructure of concrete are involved.

Studies related to the use of MW to improve concrete properties and performance

Two forms of Cement-based adhesive (CBA) were developed by Al-Safy et al. (2019) employing MW for mixing and curing. For the purpose of MW, two magnetic devices (MD-I and MD-II) were utilised, each producing a magnetic field of 9000 or 6000 Gauss. It was revealed that MW therapy boosts CBA's efficiency. The paramount results were exposed after 15 min of circulation time using 0.1 m^3/hr of modest flow rate when MD-I was deployed to MCBA samples. Furthermore, an increase in the operational time from 15 to 60 min had a useful consequence on MCBA characteristics, signifying that the latter may be more imperative. Prakash et al. (2019) introduced the concept of how MW can influence the plasticity and strength features of concrete. The researchers magnetised the water and dye wastewater. The water's chemical and physical features have been assessed. The purpose was to advance water quality to acceptable norms and decline the W/C ratio, besides the opportunity to drop the cement content used. The compressive strength tests of concrete samples immersed in MW have established an upgrading over those immersed in RTW. The impact of MW on the durability of concrete was evaluated by Sabapathy et al. (2019). Cubes of concrete mixed with MW were placed to the test. The compressive strength of concrete was established to be amplified in contrast to concrete made using RTW. When the cubes are formed using MW to get the essential compressive strength, less cement is necessary.

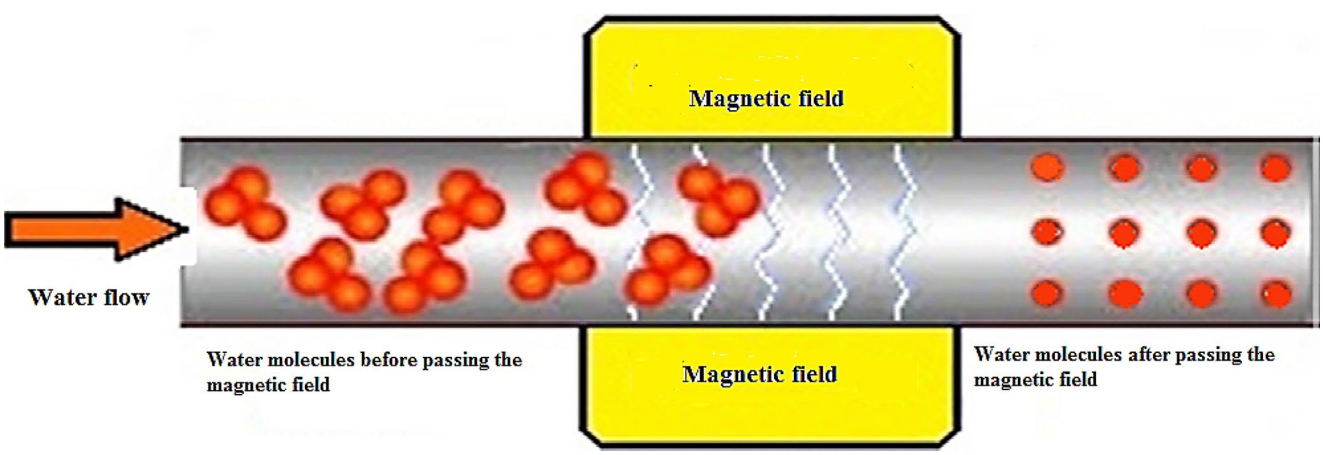

Fig. 1 Magnetization process of water (Jouzdani & Reisi, 2020)

Karthik et al. (2019) used traditional cementitious materials such as green, high performance MW concrete. The self-compacting concretes (SCCs) were made using sulphate-resistant cement (SRC), metakaolin, fine aggregate, coarse aggregate, micro steel fibres, superplasticizer, and water. The results of SCC with MW were contrasted against those of SCC and regular tap water. The findings indicated the advantage of SCC made with MW. The workability, tensile strength and compressive strength were all enhanced at a 6.74% cheaper cost. By partially replacing cement with dolomite powder, Reddy and Rao (2019) considered the effect of MW on the mechanical features of concrete. The mechanical characteristics of concrete can be affected by magnetic fields, where the magnetic fields can alter the structure and behaviour of water molecules. The sand was utilised in the mixing process, and water was magnetised by laying it on 1 T of MFI for 24 h. Specifically, 5 different M25 mixes were made using RTW and variable amounts of dolomite (by weight) were substituted for the cement.

The influence of MFI and water flow rate (Q) in an electromagnetic field on the mechanical features of self-compacting concrete (SCC) were examined by Jouzdani and Reisi (2020). Using regular or MW, the researchers made four different types of SCC bases while using different ratios of W/C (0.35, 0.4, 0.45, and 0.5). The results indicated that the use of MW can improve the mechanical properties of SCC while making the concrete less problematic to work with if compared to the use of RTW. Figure 2 depicts that the compressive, bending, and tensile strengths of concrete were enhanced by 34.1%, 52.4%, and 74.2%, respectively, although that the mixes had the same W/C ratios.

Using SCC supported with steel fibres in varying proportions, Ghorbani et al. (2020) studied the influence of MW on the fresh and hardened features of the material. This was accomplished by passing the water used in the mixing process via a stable magnetic field at MFI of 0.65 T, either once or fifteen times using a flow rate of 0.75 m/s, which resulted in a total of twelve mixes with variable steel fibre concentrations of 0%, 0.35%, 1%, and 1.65% by volume of concrete. Also, multi-expression programming, a unique evolutionary programming approach, was employed to build mathematical models. According to Fig. 3, SCC specimens made with MW have considerably greater flexural strength than specimens made with or without steel fibers.

Venkatesh and Jagannathan (2020) directed an experimental inspection of the influences of MW on the workability and strength features of concrete. The water is magnetised at either 0.986 or 2 T in the static treatment method. The objective was to reduce the cement content and porosity in concrete by optimising the water-cement ratio. After 24 h of magnetization, water used to make concrete passed tests of compressive, split tensile, and flexural strength. Using MW, the strength of concrete was improved compared to the concrete that has been prepared with RTW.

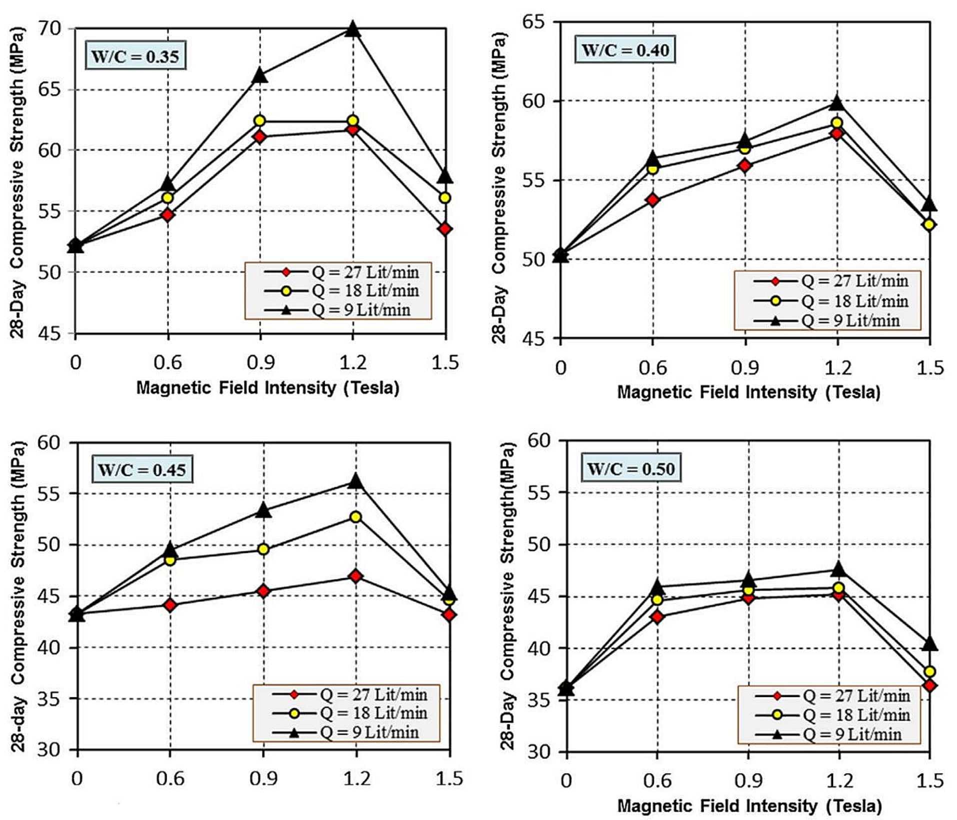

Fig. 2 28-day compressive strength of SCC against MFI at different W/C ratios and water flow rates (Jouzdani & Reisi, 2020)

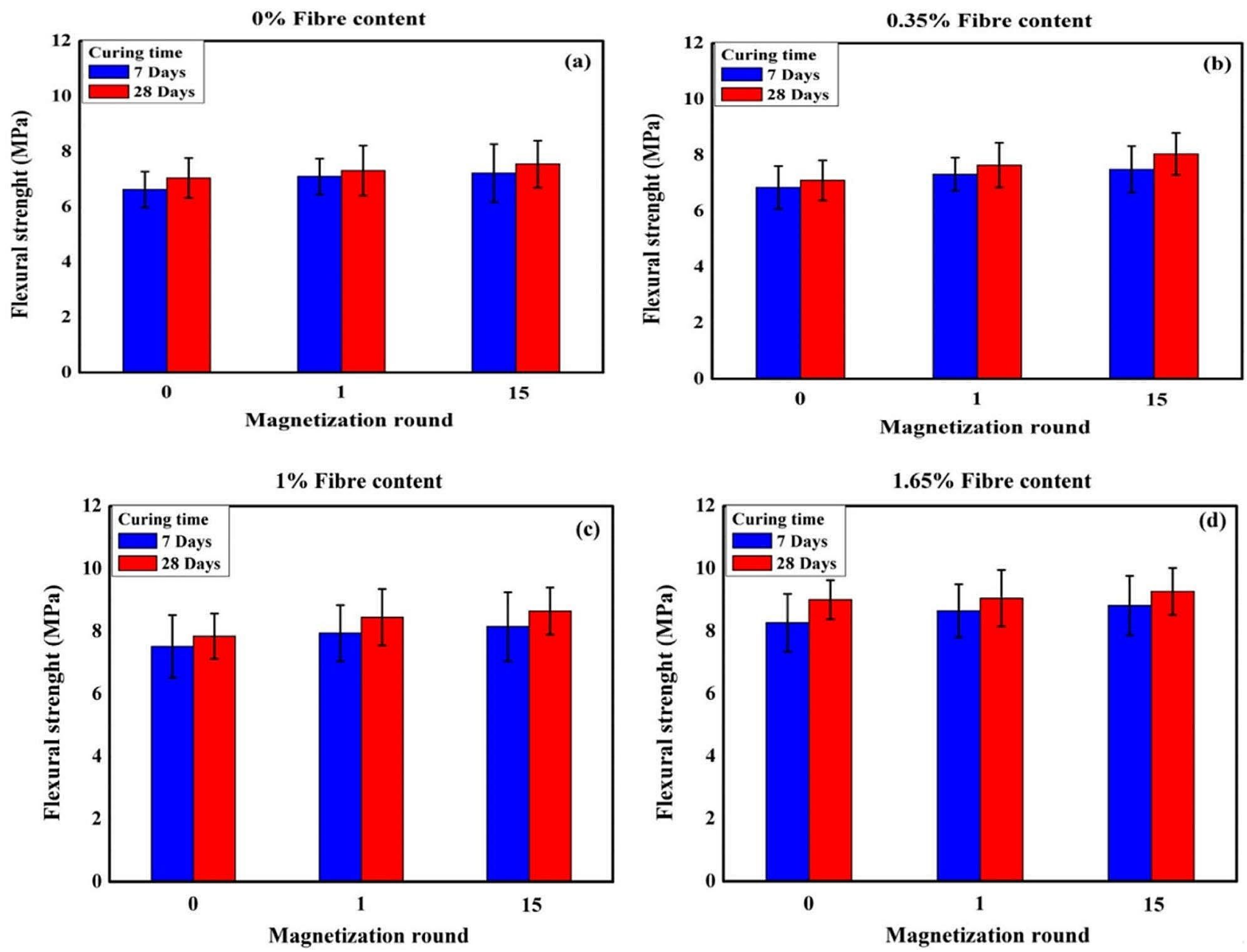

Fig. 3 Flexural strength of SCC samples against magnetization round using 0%, 0.35%, 1%, and 1.65% steel fibres produced with MW and RTW (Ghorbani et al., 2020)

Nwofor and Alabintei (2020) appraised the mechanical characteristics of concrete made with both regular tap water RTW and magnetic water MW using the magnetic pole on MW concrete. The results of the experiments elaborated that using MW in the concrete can make notable enhancements of 30% in slump, 7.6% in water absorption rate, and 15% in compressive strength. The effects of deploying mixing water of MW in concrete on compressive strength, workability, and necessary cement content were considered by Al-Maliki et al. (2020). Both MW and standard (non-magnetized) RTW were used to make concrete mixes, and the results were compared. The results revealed that the concrete was marginally easier to work with MW than concrete made with RTW. The compressive strength of concrete was also presented to be considerably increased at all the covered mix types (three different mixture types C20, C25, and C30) due to using MW at a variety of curing ages. Using MFI of 1.3 T, concrete compressive strength was increased between 3 and 17% where C30 has the optimum improvement. Divya (2020) looked at the influences of MW on the flexibility, consistency, compactivity, and tensile strength of concrete. A 0.5 hp motor with 0.9 T of MFI at the input pipe magnetises the water. Then, the authors mixed the concrete with some MW and some RTW and let it cure. Ghorbani et al. (2021a) investigated the fresh, hardened, and durability features of mortar mixes to ascertain the combined impact of Marble Waste Dust (MWD) and MW. The findings demonstrated that MW enhanced the mortar mixes' fresh, toughened, and durability qualities. However, the strength and durability of the mortar mixes are compromised as a result of the high-porous microstructure that follows from the use of additional MWD. Figure 4 shows that after 28 days of curing, the CS of mortar mixes made with MW and 0%, 10%, 20%, 30%, and 40% MWD as partial replacement of cement (PRC) improved by 32%, 21%, 17%, 26%, and 6%, respectively.

Ghorbani et al. (2021b) examined the effects of Granite Waste Dust (GWD) as PRC and MW on mechanical and durability features after exposing concrete specimens to two severe surroundings, including NaCl and H_2SO_4 solutions.

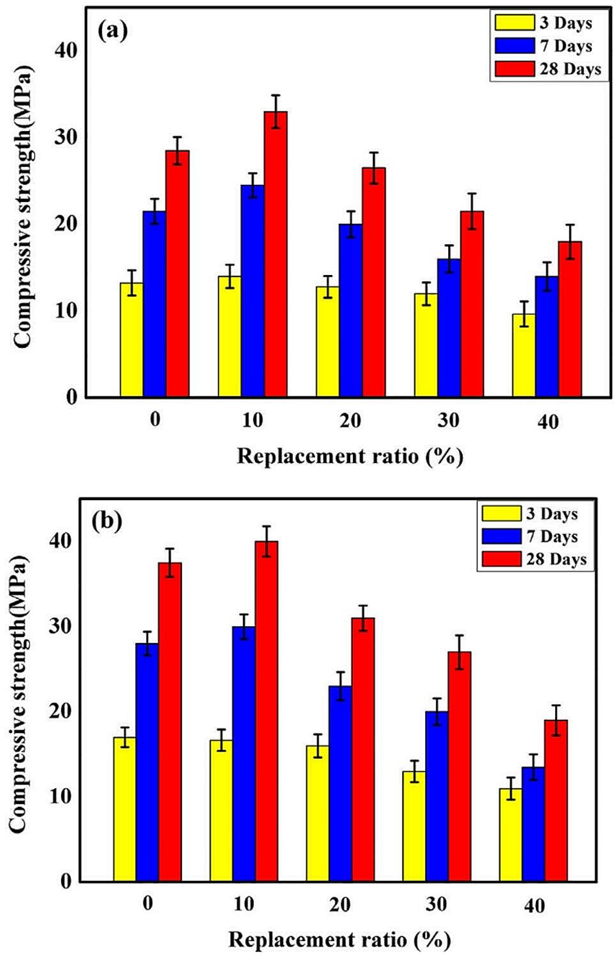

Fig. 4 MWD as PRC mortar mixes with RTW and MW (Ghorbani et al., 2021a)

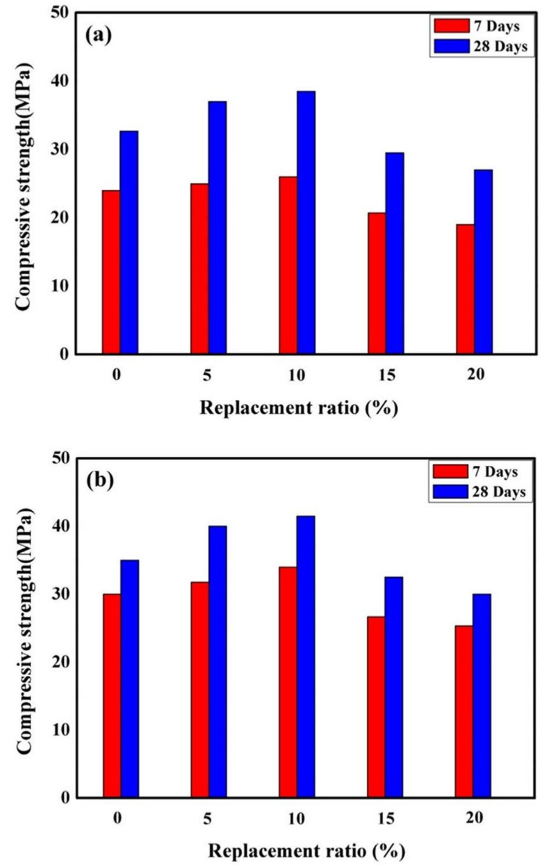

Fig. 5 Compressive strength against replacement ratio of concrete mixes containing GWD as PRC in lime-saturated water after 7 and 28 days for two cases of (**a**) TW and (**b**) MW (Ghorbani et al., 2021b)

Ten batches of concrete were made, using RTW or MW, with GWD ratios ranging between 0 and 20%. No matter what percentage of GWD was used, the findings demonstrated that utilising MW has enhanced the mechanical and durability features of the concrete. Figure 5 depicts that both the compressive strength of TW and MW specimens rose as curing went on, albeit at various rates.

The consequence of MW on the compressive strength and plasticity of concrete was considered by Narmatha et al. (2021). The magnetic treatment system was utilized to create the MW. The quantity of cement needed to attain desired compressive strengths may be reduced by using MW. A 0.5 hp engine with a PERMAG N406 0.8 T magnet at its intake pipe was deployed to magnetise the water. MW has improved the mix's splitting tensile strength and compressive strength during both the mixing and curing processes. Washing sand using MW (intensity of 9000 Gauss) was introduced by Ibrahim and Abbas (2021) as a prospective solution to the concern of high sulphate (SO_3%). The physical characteristics of splitting tensile, compressive, and flexural strengths of three batches of regular concrete were evaluated. At 7, 28, and 90 days, mixes with high sulphate levels showed a reduction in compressive, flexural, and splitting tensile strength by 1.27, 0.66, and 1.21%, respectively, relative to the control mix. The mechanical and durability characteristics of concrete were examined by Dharmaraj et al. (2021). Compression, flexural, and tensile strengths, as well as SEM analyses, were amongst the mechanical features tested. The durability tests comprised examinations of the material's capacity to endure water absorption, acidity, and corrosion. Experiments indicated that using MW to cure and prepare concrete can improve mechanical qualities and longevity. By substituting MW for RTW, Ariz and Zala (2021) increased the strength of concrete and brought it up to specification. A controlled experiment is designed to examine the influences of MW under variable conditions, such as the length of time the water spends in the magnetic field. The results showed that mixes blended with MW were more workable and had superior compressive and flexural strengths compared to the mixture that was mixed with RTW. Capillary rise via pores was also shown by the Sorptivity test applied to spherical discs.

Using a multi-criteria decision-making approach, PourNowruz (2021) analysed the effects of MW on both structural and non-structural concretes. Their experiments showed that the presence of MW has augmented the compressive strength of concrete by 28% after 28 days. Furthermore, the slump was also improved by 30%. MW was formed by Ruby and Vasudev (2021) by placing RTW through magnetic fields of various MFIs of 0.6 T, 0.8 T, 1.0 T, and 1.2 T. MW might be seen as a cutting-edge approach to dropping the wasteful use of potable water in the building. The effect of MW in the considerable MFIs on fly ash as a percentage of cement weight (fresh and hardened characteristics) was considered. Using a magnetic field and without, Keshta et al. (2022a) experimentally evaluated the feasibility of using Volcanic Ash (VA), a supplemental cementitious ingredient, in the development of sustainable concrete. Thirty different mixtures were made using VA in five different proportions of 0, 5, 10, 15, and 20% in lieu of cement. To compare various magnetization strategies, MW was produced with 1.6 T and 1.4 T of magnetic intensities.

RTW and cement grout were magnetised using a lab-built magnetization apparatus created by Hu et al. (2022). Using MW, the authors made samples of cement grout with 0.5 and 1 of W/C ratio. The permanence of the cement grouts mixed with RW and MW was appraised. The findings proved that MW improves the durability of cement grout. Depending on the magnetization conditions, cement grouts with a 0.5 and 1 W/C ratio exhibit stability augmentation ratios of 5-67.31% and 0.58–24.16%, respectively. To enhance workability and strength, Abbas et al. (2022) substituted the MW treatment system for RTW in the preparation of concrete mixtures. SCC with a grade of 35 MPa was chosen, and regular concrete production with two grades of 25 and 35 MPa was used. The mutual influence of MW and superplasticizer in SCC, however, showed the greatest enhancement for 35 MPa grade with diminished water content; the latter was only apparent when the water content to cementitious substance was elevated. Figure 6 shows the relative improvement in flexural strength between concrete mixes using MW and those using RTW.

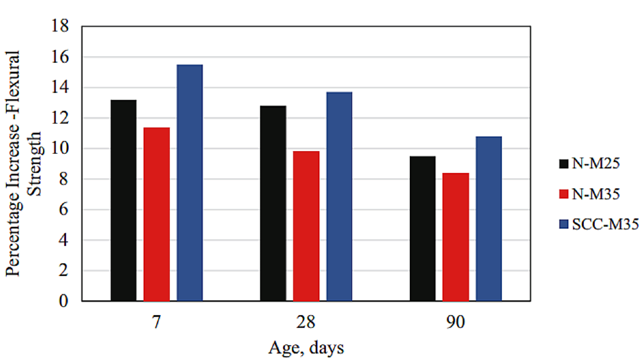

Fig. 6 Improved percentage of flexural strength for three mixes using MW and RTW (Abbas et al., 2022)

The impact of MW produced in a magnetic field of MFI of 1.4 T on the plasticity and hardened characteristics including the tensile, compressive, and flexural strengths of VA concrete was investigated by Keshta et al. (2022b). At variable percentages of 5%, 10%, 15%, and 20%, VA was used in lieu of volcanic concrete cement. Two sets of ten different volcanic concrete mixtures were synthesised. The first one was made using VA that was diluted with RTW between 0% and 20%. The second group also had the same amount of VA as the first, but it was combined with MW during preparation. When using RTW, the slump of the volcanic concrete was reduced; when using MW, the slump increased by as much as 8%. Without VA and with MW present, the compressive strength augmented by 35% after 7 days, 23% after 28 days, and 20% after 120 days. The effect of MW on the mechanical features of expanded polystyrene-based lightweight concrete (LWC) was evaluated by Holakoei and Sajedi (2022). There were eight discrete waters used. MW at MFI of 0.5, 1, and 2 T, the water used was both RTW (drinking water) and raw Karun River water. The results indicated that using MW from RTW generated more mechanical features than using MW from river raw water. The consequences of MW and fly ash on the mechanical and durability features of concrete were considered by Rao et al. (2023). The multiple measurements of pH, acidity, alkalinity, chlorides, and Total Dissolved Solids (TDS) in both RTW and MW were accompanied while using a 1.5 T. Cement has been used to exchange fly ash at replacement rates of 10 wt%, 20 wt%, 30 wt%, and 40 wt%. The outcomes proved that the ideal amount of fly ash is 30% and the inclusion of MW in the concrete mix has caused a growth in the compressive strength by 38.46%. Preethi et al. (2023) tested a number of physical properties for samples of MW. These comprise the tensile strength, compressive strength, and flexural strength. The experimental findings showed that concrete samples mixed with MW were much stronger than those mixed with RTW. The effect of magnetised seawater on the durability of standard-grade concrete was elucidated by Naveen et al. (2023). Efflorescence and reinforcement corrosion are the results of using regular seawater in concrete. In this regard, the effects of magnetised seawater on the durability of M25 and M30 concrete are investigated. MW and magnetic seawater ($CaCl_2$) were produced by magnetising RTW and saltwater with 985 gauss magnets, respectively, before using them to mix concrete. Nadgouda et al. (2023) evaluated a set of mechanical properties including the workability, durability, tensile strength, compressive strength, and flexural strength of concrete while using magnetic water. The results indicated that concrete made with MW had greater tensile strengths by 7–27%, flexural strengths by 10–14%, and compressive strengths by 10–23% if compared to concrete equipped with RTW. Positive consequences were acquired when MW was substituted at concentrations ranging between 30 and 90% of the total volume of the specimen. The effect of utilising MW as an alternative to RTW on the mechanical qualities of concrete exposed to a high temperature was studied by Barham et al. (2023). Both batches of concrete utilised the same components. In the first mixture, RTW was utilised, whereas in the second, MW was used. There were 48 casts overall, and they were split up as follows: The concrete compressive strength test required 16 cylinders (8 specimens for each mix), the splitting tensile strength test required 16 cylinders (8 specimens for each mix), and the flexural strength test required 16 beams (8 specimens for each mix). Table 1 presents a summary of conducted investigations on MW to improve the physical properties performance and interaction features of concrete.

Studies related to the use of MW to improve microscopic and interaction features

Ghorbani et al. (2019a) carried out thorough tests to ascertain the impact of MW on foam stability, splitting tensile strength, compressive strength, water absorption, and the microstructure of foam concrete. When RTW was exposed to a permanent magnetic field five or ten times, respectively, the results revealed that the compressive strength of the foam concrete specimens was raised by about 40% and 50% after 28 days of curing (Fig. 7). Particularly for the samples with a flow rate of 0.75 m/s, this was accurate. After 3, 7, 14, and 28 days of wet curing, respectively, the splitting tensile strength of foam concrete specimens treated with MW that had been passed through a long-lasting magnetic field ten times at a flow rate of 0.75 m/s rose by 70%, 70%, 50%, and 44%.

Ghorbani et al. (2019b) investigated how MW affected the resilience of synthetic and protein-based foam agents as well as foam concrete. Three different volumes of foam were generated at three different flow rates of MW of 0.75 m/s, 1.75 m/s, and 2.75 m/s. Foam concrete samples were made using a synthetic basis utilising a volumetric ratio of 1/30 and the aforementioned three water flow rates. The authors proved that synthetic foams were far more stable in the long run than their protein-based counterparts. Figure 8 demonstrates how, when the water passes through the permanent magnetic field more times, foam concrete mixtures with slower flow rates become more stable.

Ghorbani et al. (2019c) sought to evaluate the foam stability, splitting tensile strength, compressive strength, water absorption, and microstructure of foam concrete. Water flowing between 0.75 and 2.75 m/s via a persistent magnetic field was used to synthesize nine different mixtures with variable degrees of magnetic properties. According to the findings of the tests, utilising MW has considerably increased the aforementioned mechanical properties of foam concrete, while mitigating the water absorption of the hardened foam concrete. Compressive strength and bond strength were studied by Barham et al. (2021) as a function of the amount of silica fume and the magnetic field treatment of the water used to make the concrete. Ninety samples were cast and put through a battery of tests, including compression and pullout. The findings demonstrated that the compression strength was meaningfully improved when MW was employed despite the presence of silica fumes. At 7 days old, Fig. 9 shows that the compressive strength of the M-S15 and N-S15 specimens, which contain 15% and 45% and 0% replacement of silica fume, respectively, is greater than that of the M-S0 and N-S0 specimens.

The effectiveness of CRC with a high concentration of heat-pretreated rubber and MW, manufactured in 1.4 T of MFI was experimentally studied by Youssf et al. (2022). The authors controlled a number of parameters including the rubber concentration, heating duration and temperature, MW concentration, and water magnetising time. Under these circumstances, using a rubber component of 40% restored 74% of the material's compressive strength, increased impact resistance by 2.2 times, and increased impact resistance by 92%. Ramalingam et al. (2022) used physiochemical analysis to compare the MW at various contact times including 60 min (MW60), 45 min (MW45), 30 min (MW30), 15 min (MW15), and instant contact (MWI) to water quality standards. The findings revealed that the concrete qualities have been improved significantly with longer periods of exposure to the magnetic influence on water characteristics. The MW60 mix improved upon the RTW concrete in both workability and compressive strength, by 25.6% and 24.1%, respectively. SCC fresh, mechanical, and microstructural characteristics were enhanced by MW, as reported by ELShami et al. (2022). There were 12 different mixes made, each with a different percentage of silica fume (5 wt% and 10 wt% of cement), and the water used in the mixing process was subjected to a steady magnetic field of 1.4 T for 50, 100, and 150 cycles. Mix M8, with 5% silica fume and 150 MW cycles, produced the highest compressive strength. SEM and EDX studies showed that SCC mixes made with MW had more C-S-H, less CH, and were denser. Table 2 introduces a summary of conducted investigations on MW to improve the microscopic and interaction features of concrete.

Table 1 A summary of conducted investigations on MW to improve physical properties, performance and interaction features of concrete

Authors (year) [reference]	Studied parameters	Type of study	Results
Al-Safy et al. (2019)	Impact of MW therapy on CBA efficacy.	Experimental	It was discovered that MW therapy boosts CBA's efficacy. When MD-I was applied to MCBA samples, the best results were shown after 15 min of circulation time with 0.1 m^3/hr of water flow rate.
Prakash et al. (2019)	The consequence of MW on the plasticity and strength of concrete.	Experimental	Samples of MW-produced concrete demonstrated higher compressive strengths than RTW-produced concrete.
Sabapathy et al. (2019)	Impact of using MW on the durability of construction materials.	Experimental	The weight of a concrete cube was lowered by about 13% using MW. A 20% increase in concrete's compressive strength can be achieved by adding MW to the mix. Additionally, using MW in the production of concrete can significantly reduce the quantity of cement used, saving on expensive and environmentally harmful cement.
Karthik et al. (2019)	Effect of MW on the physical characteristics of SCC.	Experimental	When compared to SCC made with RTW, MW-prepared SCC had somewhat better workability, slightly greater compressive strength, slightly higher tensile strength, and a 6.74% cheaper price.
Reddy and Rao (2019)	Impact of MW on the mechanical features of concrete, with dolomite powder used to partially replace some of the cement.	Experimental	When compared to mixes made with RTW, those made using MW had more potency.
Jouzdani and Reisi (2020)	Effect of MFI and water flow rate on the mechanical characteristics of SCC.	Experimental	When MW was used instead of RTW, the mechanical features of SCC were improved, as was the workability of concrete. The most significant effect of MW was demonstrated, leading to a 34.1% decrease in the use of superplasticizer at MFI = 1.2 T and Q = 9 L/min.
Ghorbani et al. (2020)	Impact of MW on the fresh and hardened characteristics of steel-reinforced SCC.	Experimental and numerical	The SCC mixes are significantly improved by utilising MW.
Venkatesh and Jagannathan (2020)	Influence of using MW on the workability and strength of concrete.	Experimental	The strength of concrete that has been formed using MW is superior to that of concrete that has been prepared with RTW.
Nwofor and Alabintei (2020)	Effect of using MW with the presence of a magnetic pole on the slump, compressive strength, and water absorption of concrete compared to RTW.	Experimental	The concrete made from MW utilising mixed poles (both north and south) had a greater compressive strength (27.22 N/mm^2) and a lower water absorption rate (10.02%) than the concrete made from MW using only one pole.
Al-Maliki et al. (2020)	Effect of adding MW to concrete considering the mechanical properties and necessary cement content.	Experimental	At an MFI of 1.3 T, the compressive strength of the C30 concrete type was improved by 17%.
Divya (2020)	Impact of MW on the fluidity, consistency, compactness of concrete and strength under compression.	Experimental	MW concrete has a compressive strength that is 22% greater than RTW concrete. The percentage increase in strength of concrete made with MW is greatest at 1, 3, and 7 days after mixing.
Ghorbani et al. (2021a)	Effects of MW and MWD on the fresh, hardened, and durability qualities of mortar mixes.	Experimental	Adding MW to mortar mixtures enhanced their fresh, firm, and long-lasting qualities. Due to a more porous microstructure, the strength and durability of mortar mixes suffer when MWD is added in greater quantities.
Ghorbani et al. (2021b)	Impact of MW on the mechanical and durability qualities of concrete samples subjected to NaCl and H_2SO_4 solutions, and the use of GWD as a PRC.	Experimental	Regardless of the type of water used, excessive GWD lowers cement content and creates a more porous microstructure, which lowers the samples' strength and durability indices.
Narmatha et al. (2021)	Effect of MW on the plasticity and strength of concrete.	Experimental	During the mixing and curing phases, MW increases the mixture's compressive strength and splitting tensile strength.
Ibrahim and Abbas (2021)	The effectiveness of MW in reducing high sulphate- (SO_3) levels.	Experimental	If compared to the control mix, mixes with high sulphate levels showed reductions in compressive, flexural, and splitting tensile strength at 7, 28, and 90 days of 1.27%, 0.6%, and 1.2%, respectively.
Dharmaraj et al. (2021)	The consequence of using MW on the mechanical characteristics of mixed concrete.	Experimental	Using MW for mixing and curing concrete has enhanced its mechanical qualities and longevity. The compressive strength of MW concrete is 14.86% greater than that of RTW concrete.
Ariz and Zala (2021)	The advantages of using MW in place of RTW for strengthening concrete.	Experimental	The combination that was combined with MW had superior compressive and flexural strengths compared to the mixture that was mixed with RTW.

Table 1 (continued)

Authors (year) [reference]	Studied parameters	Type of study	Results
PourNowruz (2021)	Effect of MW on the compressive strength of concrete.	Experimental	The slump was enhanced by 30% when mixed with MW, and the compressive strength was increased by 28% after 28 days.
Ruby and Vasudev (2021)	Influence of MW on the fresh and hardened characteristics of fly ash in cement using different MFI	Experimental	Using MW has an advantageous consequence on the improvement of the characteristics of concrete.
Keshta et al. (2022a)	Effect of MW on the compressive strength of concrete.	Experimental	The compressive strength is enhanced by 24% after 7 days using 5% VA and RTW, and by 22% and 33% when using MW and 5% VA.
Hu et al. (2022)	Influence of magnetic state on the strength of cement grout containing MW.	Experimental	0.5 to 1 of W/C ratios of cement grouts have stability improvement ratios between 5% and 67.31% and 0.58% and 24.16%, respectively, depending on the magnetization circumstances.
Abbas et al. (2022)	Impact of using MW on the physical characteristics of splitting tensile, compressive, and flexural strengths.	Experimental	Even though the combined influence of MW and superplasticizer in SCC presented the greatest enhancement with less water content for 35 MPa grade, the latter was only noticeable when the water content to cementitious substance was raised.
Keshta et al. (2022b)	Impact of using MW in an MFI of 1.4 T on the volcanic workability of concrete and hardened qualities	Experimental	Without VA and with MW present, the compressive strength improved by 35% after 7 days, 23% after 28 days, and 20% after 120 days. Compressive strength increased by 11% after 7 days, 12% after 28 days, and 11% after 120 days when 5% VA was used in conjunction with MW.
Holakoei and Sajedi (2022)	Impact of MW on the mechanical characteristics of expanded polystyrene lightweight concretes.	Experimental	Compressive, tensile, and flexural strength, as well as electrical conductivity, were all found to rise by 24.4%, 6.1%, 3.9%, and 0.5%, respectively, in concretes created with MW of drinking water, and by 12.4%, 3.6%, 3.4%, and 2%, respectively, in concretes made with MW from river raw water.
Rao et al. (2023)	The mechanical and durability benefits of using MW and fly ash in concrete.	Experimental	When MW was incorporated into the concrete mix, the compressive strength increased by 38.46%, and 30% fly ash was determined to be the appropriate amount. Additionally, MW in concrete has the potential to considerably increase the material's durability.
Preethi et al. (2023)	Effect of MW on the tensile, compressive, and flexural strengths of MW-based concrete samples.	Experimental	Concrete samples formed with MW were far more durable than those made with just RTW.
Naveen et al. (2023)	Effect of magnetised seawater on the compressive strength of concrete over time.	Experimental	MW has a somewhat greater influence on the workability of concrete. Concrete mixed with MW or magnetised salt water is somewhat easier to work with than concrete mixed with RTW or regular salt water.
Nadgouda et al. (2023)	Impact of MW on the split tensile strength, flexural strength, compressive strength, and workability of concrete.	Experimental	Positive results were obtained when MW was substituted at concentrations ranging from 30–90% of the total volume of the specimen. Additionally, it has been discovered that the application of MW progresses the slump, fluidity, and degree of hydration of concrete.
Barham et al. (2023)	Impact of switching to MW from RTW on the mechanical features of concrete exposed to high temperatures.	Experimental	The splitting tensile strength, compressive strength, and flexural strength of concrete specimens cast and prepared with MW are superior to those of RTW specimens of concrete at all temperatures. For the MW and RTW, the compressive strength ranged from 110–123%, while the splitting strength ranged from 110–133%.

Critical evaluation of utilising MW in the concrete industry instead of RTW

This section intends to present the standpoints of the authors towards the involvement of MW in the concrete industry and the most common challenges encountered with the utilisation of RTW in concrete production.

The MW technology has recently attracted a lot of scholarly interest. Results from tests of splitting tensile strength, compressive strength, and flexural strength all favored the use of MW. However, a clear discrepancy between the outcomes of these studies can be noticed. Up to the authors' knowledge, the differences in MFI, treatment time, and water composition can be attributed to this. Given the potential for enhanced mix designs and lower cementitious material usage, MW treatment might reduce the amount of cement required for concrete production or increase its performance. Indeed, any decrease in cement use could have a positive impact on the environment because cement manufacture is linked to high energy use and greenhouse gas emissions. In this regard, it has been reported that using MW can reduce the amount of used cement by 12.5–22.2%

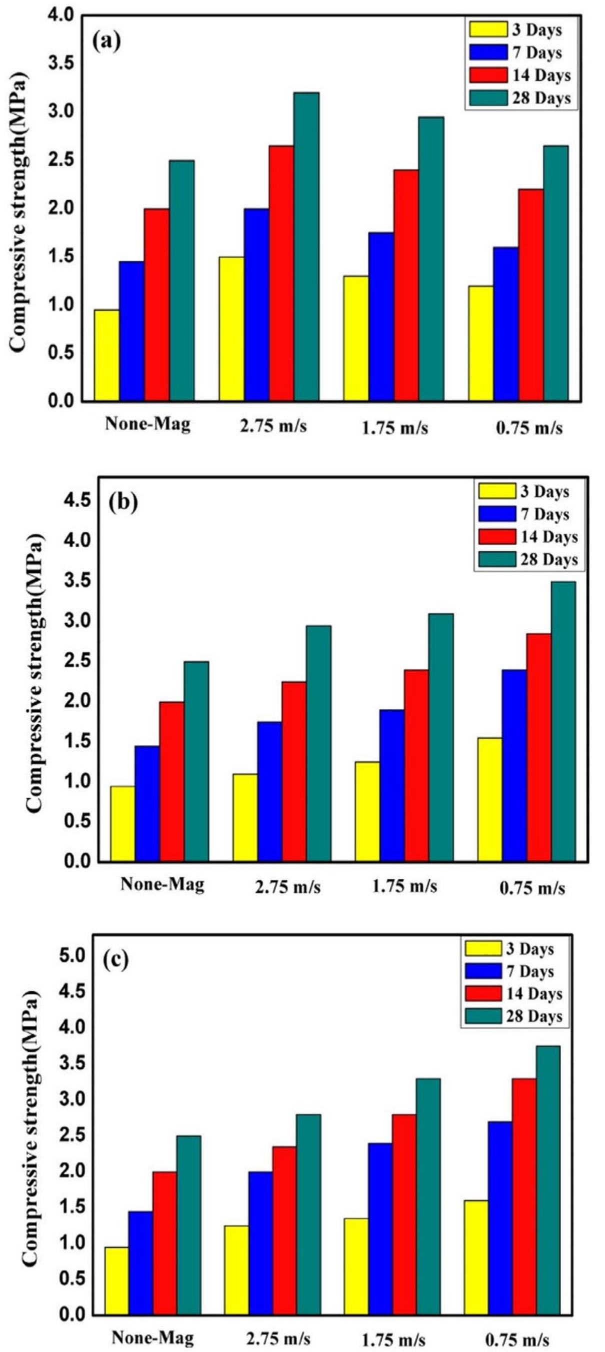

Fig. 7 Comparison between compressive strength against flow rate of magnetic and non-magnetic foam concrete specimens considering three cases of using the permanent magnetic field of (**a**) 1, (**b**) 5, and (**c**) 10 times (Ghorbani et al., 2019a)

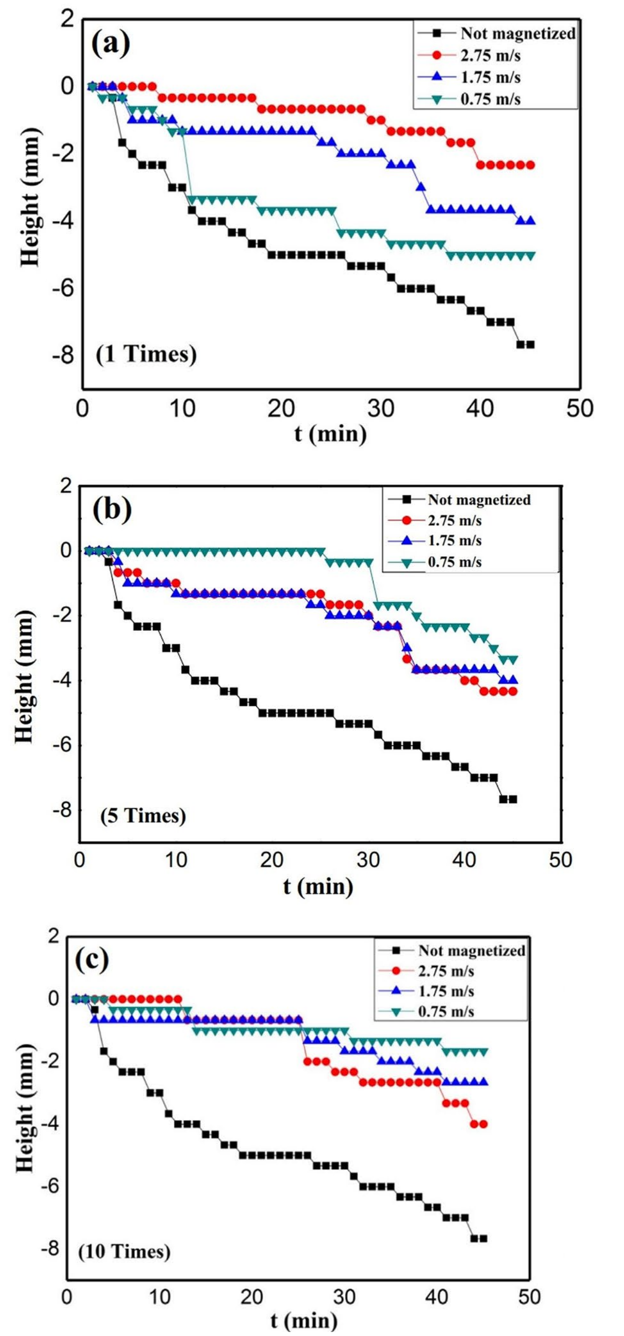

Fig. 8 Foam concrete height against elapsed time for different flow rates of MW considering three cases of passing through the magnetic field of (**a**) 1, (**b**) 5, and (**c**) 10 times (Ghorbani et al., 2019b)

compared to non-magnetic water (Afshin et al., 2010). According to a number of experiments conducted by Afshin et al. (2010) in the concrete laboratory of Sahand University of Technology, 50 and 100 kg of cement can be saved in a cubic meter of concrete while using different mixture designs based on magnetic water. This improvement can be attributed to the change in physical properties due to passing water through a magnetic field.

NGENE et al. (2019) ascertained that the water quality can be enhanced by breaking down the molecules into single or finer forms by the magnetic force of the field. Specifically, the diamagnetism of the hydrogen bond has caused certain changes in the characteristics of water, which in turn produces increased stability in a magnetic field.

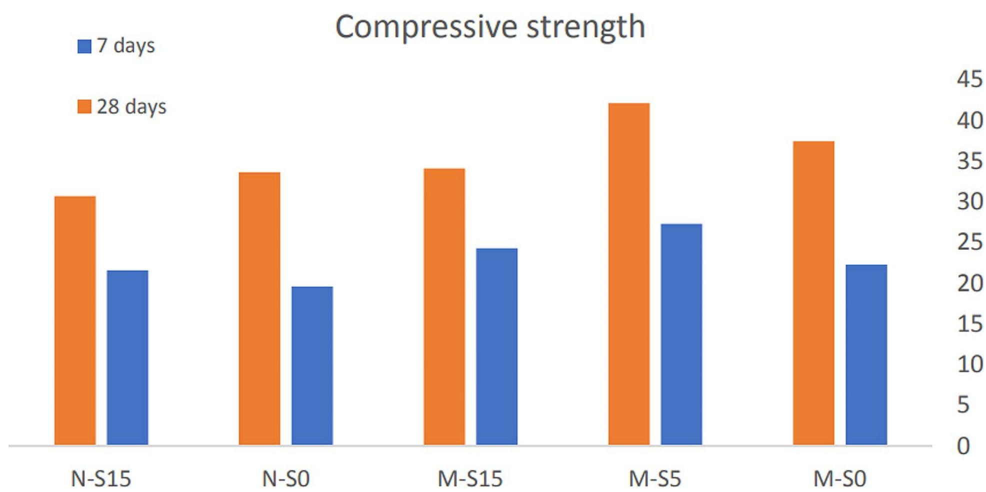

Fig. 9 Compressive strength of 7 and 28 days (Barham et al., 2021)

Table 2 A summary of conducted investigations on MW to improve microscopic and interaction features of concrete

Authors (year) [reference]	Studied parameters	Type of study	Results/Findings
Ghorbani et al. (2019a)	Effect of MW on foam microstructure, water absorption, splitting tensile strength, and compressive strength of concrete.	Experimental	Utilising MW significantly reduces the water absorption of cured foam concrete while increasing the foam stability, breaking tensile strength and compressive of foam concrete.
Ghorbani et al. (2019b)	Contribution of foam concrete and foam agents with both synthetic and protein bases in the presence of MW.	Experimental and numerical	Protein-based foams lost stability in MW whereas synthetic-based foams gained stability. Additionally, the inclusion of MW increased the stability of the synthetic-based foam concrete relative to the control mix.
Ghorbani et al. (2019c)	Effect of MW on foam microstructure, water absorption, compressive strength, and mechanical properties of concrete.	Experimental	Using MW considerably increases the foam stability, tensile strength and compressive of foam concrete, while decreasing the water absorption of foam concrete.
Barham et al. (2021)	Compressive and bond strengths of concrete with 25% silica fume and a magnetic field.	Experimental and numerical	No matter how much silica fume was added, the compression strength was significantly improved by using MW. Also, the bond strength of samples obtained with MW was greater than that of samples obtained with ordinary water.
Youssf et al. (2022)	Impact on CRC efficiency of heat-pretreated rubber and MW.	Experimental	Pre-heating the rubber increased its compressive strength and impact resistance while also removing the majority of the unfavourable components from the rubber aggregate, forming a hard outer shell around the rubber particles, and lowering the zinc content from 8.32–1.89%.
Ramalingam et al. (2022)	Effect of magnetism on the microstructural behaviour of concrete and physical properties of water used in concrete.	Experimental	As the period of exposure to the magnets increased, the concrete's qualities improved noticeably due to the magnetic influence on water. The MW60 mix improved upon the NWC in both workability and compressive strength, by 25.6% and 24.1%, respectively.
ELShami et al. (2022)	Effect of MW on SCC fresh, mechanical, and microstructural of SCC.	Experimental	Mix M8, with 5% silica fume and 150 MW cycles, produced the highest compressive strength. SCC mixes made with MW had more C-S-H, less CH, and were denser.

Notwithstanding the advantages of using chemical admixtures in the concrete industry, MW technology diminishes the need for chemical admixtures like high range water reducing superplasticizers, complex concrete forms like epoxy concrete, and the use of additives like fly ash to increase strength. In other words, by employing MW in the manufacturing of concrete, the workability and strength of the concrete are augmented without the need for additional water or ingredients. Thus, the MW method enables the production of low-cost, and high-strength concrete. Obviously, the MW technology is a simple and non-sophisticated process that requires only a permanent magnetic field without needing a source of energy. However, this is an uncommon sector where there are not any established standards. Also, the MW technology is a time-consuming process that requires considerable hours to ensure the full magnetization of stagnant water. Therefore, if MW is employed, concrete mix design and quality control techniques may need to be modified, necessitating extensive research and validation.

Despite the hypothesized benefits of utilising magnetic water in concrete technology based on early research and theoretical considerations, there are still a number of challenges and limitations. Specifically, there is still a lack of comprehensive research to fully perceive the long term effects of magnetic water and optimal application in the concrete industry. Critical examinations are therefore required to evaluate the influences of treatment duration, magnetic field strength, and water composition on the concrete quality. Recently, Guelmine (2023) ascertained the challenges of having precise control of the exposure time and magnetic field intensity in the utilisation of magnetic water. The gradual diminishing of the magnetic effect after treatment and the uncertainty of complete loss can also pose a challenge in utilising magnetic water (Mohammadnezhad et al., 2022). This might be attributed to the reason for the absence of large-scale construction projects of concrete based magnetic water. Furthermore, further cost is required to establish the equipment and infrastructure to carry out the magnetic treatment process. on top of this, the absence of standardization and guidelines imposes a barrier to extensive utilisation of magnetic water in concrete production. In summary, the practical application of magnetic water treatment in the manufacture of concrete necessitates careful scientific examination, validation, and industry consensus.

Conclusions

The recent review articulated the influence of MW on the mechanical features of concrete along with an analysis of the associated experimental and numerical studies that featured several cutting-edge techniques of advancement. The intention was specifically to expand the understanding of concrete materials science and explore the novelist strategies for improving the concrete features and concrete microstructure via the deployment of MW. Fairly, it can be said that MW technology has the potential to boost the mechanical features of concrete but is not yet ready for widespread use. The fact that the magnetization of water cannot be performed on a wide scale is the primary obstacle. Several significant conclusions can be made in the following;

1. The physical properties of concrete have been enhanced after utilizing MW with a significant increase in slump. Specifically, MW considerably has increased the foam stability, split tensile strength, compressive strength, and flexural strength of foam concrete compared to RTW concrete. For instance, compressive, tensile, and flexural strength, as well as electrical conductivity, were all found to rise by 24.4%, 6.1%, 3.9%, and 0.5%, respectively, in concretes created with MW (potable water), compared to rise by 12.4%, 3.6%, 3.4%, and 2%, respectively, in concretes made with MW (river raw water).
2. The surface tension and interactions between cement particles and water may change after MW treatment. As a result, workability and lubrication can be improved without compromising strength or durability. This is turn, can result in a higher slump value in the concrete.
3. The changing characteristics of MW might affect how cement particles hydrate, thereby resulting in effective cement hydration. This can lead to increased concrete strength development.
4. By improving cement particle water absorption using MW treatment, the overall water requirement in concrete mixtures may be decreased while enhancing the slump. In this regard, the MFI of MW is important for maximum water absorption and porosity at MFI of 1T. At an MFI of 0.9T, MW showed the highest sorptivity.
5. According to certain research, MW treatment may increase the longevity (durability) of concrete by altering pore structure, lowering permeability, and perhaps reducing sulfate attack.

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Declarations

Competing interests The authors declare no competing interests.

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