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Effect of Water Magnetization Technique on the Properties of Metakaolin-Based Sustainable Concrete

Ahmed M. Elkerany [1,2], Mohamed M. Yousry Elshikh [1], Ahmed A. Elshami [3] and Osama Youssf [1,*]

1 Structural Engineering Department, Mansoura University, Mansoura 35516, Egypt
2 Civil Engineering Department, Higher Institute for Engineering and Technology, Manzala 35642, Egypt
3 Housing & Building National Research Centre, Dokki, Giza 12611, Egypt
* Correspondence: osama.youssf@mymail.unisa.edu.au

Abstract: Using metakaolin (MK) in concrete with magnetized water (MW) has a high possibility to enhance concrete suitability. In this study, the effect of using MK and MW on concrete characteristics was studied through testing twelve concrete mixes. Seven ratios of MK were used in this study, namely 0%, 5%, 10%, and 20%, as an alternative to cement and +5%, +10%, and +20% as a cement additive. In addition, five water magnetization methods were applied on MK concrete. In the first stage of this study, the impact of different MK ratios on the workability of concrete, compressive strength, flexural strength, and tensile strength was studied using traditional tap water (TW) as the concrete mixing water. In the second stage, the best mix (best MK ratio) from the first stage was chosen to study the effect of the water magnetization method on concrete properties and to determine the best method for water magnetization. Scanning electronic microscope (SEM) analysis was also carried out on selected mixes to closely investigate the effect of MK and MW on concrete microstructure. The results showed that the best ratio of MK in concrete was +10% (MK as a 10% cement addition), and the best water magnetization method was to pass the water through 1.6 tesla then through 1.4 tesla magnetic fields. The SEM analysis confirmed the absence of pores after using MW instead of regular TW by increasing the calcium silicate hydrate (CSH) gel and reducing calcium hydroxide (CH). Using MK and MW enhanced the compressive strength by up to 33%, 32%, and 27% at 7, 28, and 365 days, respectively, and MW enhanced the workability by up to 3% compared to that of the control mix.

Keywords: magnetized water; metakaolin; SEM analysis; compressive strength; workability

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1. Introduction

Utilizing supplementary cementitious materials (SCMs) as Portland cement replacement in concrete can have positive environmental effects and relatively lower concrete production costs [1,2]. Examples of SCMs include fly ash (FA), rice husk ash (RHA), silica fume (SF), and granulated blast furnace slag (GBFS) [3–7]. By calcining kaolinite, a highly reactive pozzolanic substance known as metakaolin (MK) is produced. It is a stable product in normal environmental conditions, but when exposed to high elevated temperatures ranging between 650 °C and 900 °C, calcination takes place, and it loses 14% of its mass [8,9]. According to Heath et al. [10], producing one ton of Portland cement requires 1.6 tons of limestone and clay, while producing one ton of MK requires only 1.16 tons of kaolin [11]. High-performance, high-strength, fiber-reinforced, lightweight precast concrete products and mortars use MK to partially replace cement. In order to improve the concrete load-bearing capacities and durability, MK can enhance concrete compressive and flexural strengths, decrease its permeability, decrease the adverse effects of alkali–silica reactivity, and reduce concrete shrinkage due to its fine particles [12]. Financial and environmental advantages can be achieved when using MK in concrete [13].

To date, numerous studies on the application of MK in concrete have been conducted. Chu and Kwan [14] investigated how various MK ratios affected the mortar's fresh properties and discovered that the fresh properties of the mortar of cement with different W/CM ratios were enhanced slightly by adding 20% MK. Rashad [15] investigated how utilizing MK affected concrete workability and found that it had an adverse effect. According to Al Menhosh et al. [16], the addition of 5% polymer with 15% MK to concrete increased its 180-day tensile and flexural strengths by up to 15% without any apparent impact on compressive strength. MK's impact on the tensile strength of concrete and dynamic modulus of elasticity was evaluated by [17,18], who discovered that 20% MK in concrete increased both of these properties. The workability of recycled coarse aggregate concrete with MK slightly decreased as reported by Muduli and Mukharjee [19]. According to Chu and Kwan [14], who investigated the impact of various MK ratios on mortar's fresh qualities, 20% MK added to cement mortar with a variety of W/CMs ratios slightly enhanced the fresh properties of mortar. They attributed these enhancements to MK's better packing density and filling impact. Finally, the impact of the pozzolanic reaction of MK as a supplementary material lies in the reaction between the silica in pozzolanic material with calcium hydroxide (CH) from the hydration process of cement [20].

Recent research has used magnetized water (MW) in concrete mixtures and investigated its impacts on compressive strength, workability and other mechanical properties [21–23]. They stated that when tap water (TW) and cement were mixed together, an initial hydration process took place on the surface of cement particles. As a result, the cement particles acquired a layer of hydration products that prevented further hydration and so the concrete strength increased but not at the same rate when MW was utilized. When MW is used, molecules of water can penetrate particles of cement quickly, enabling a more thorough process of hydration that increases the concrete strength by covering all cement particles in the hydration process compared to normal TW. Toledo et al. [24] suggested that the magnetic fields weaken the intracluster hydrogen bonds, leading the greater clusters to break apart and give rise to smaller clusters with a stronger intracluster hydrogen link, as shown in Figure 1.

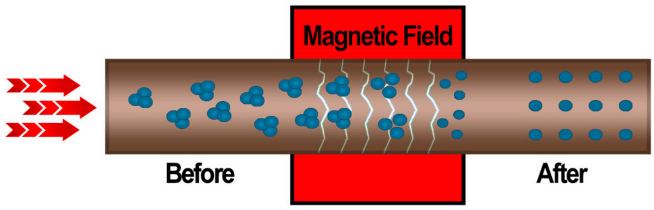


Figure 1. Effect of magnetic field on clusters of water.

Afshin et al. [25] investigated the effect of employing MW on increasing the mechanical properties of high-strength concrete. They found that the slump value of concrete mixed with MW was generally higher than that mixed with TW, and the compressive strength increased by 18%. Furthermore, the content of cement could be reduced by 27% while maintaining the concrete slump and compressive strength values utilizing MW. This was the result of penetration of MW to the overall cement content compared to using TW, which needs more cement to complete the hydration process. According to research by Abdel-Magid et al. [26], MW's application in concrete mixtures has the ability to significantly lower the amount of water needed in the concrete mixture. They stated that MW significantly increases the workability of concrete by up to 400%. As a result, compared to using regular TW, employing MW can drastically lower the amount of water needed for mixing to produce workable concrete. According to Gholhaki et al. [27], MW can boost the splitting tensile and flexural strengths of concrete. For concrete made with MW, the flexural strength and tensile strength results at 28 days were from 3.71 to 4.15 MPa vs. 3.5 MPa for the control mix. In an experimental investigation on the use of MW and volcanic ash to create sustainable concrete, Keshta et al. [28] found that the addition of MW, made at

1.4 Tesla (T) of intensity, increased the mechanical qualities of sustainable concrete by 35%. In another study, Keshta et al. [29] examined the impact of various magnetic fields on concrete compressive strength and found that employing various magnetic field intensities during the production of the MW had a favorable impact on the concrete's compressive strength. In a study on employing MW to create self-compacting concrete, ELShami et al. [30] found that MW made with 1.4 T as a magnetic field improved the self-compacting concrete's characteristics. In order to identify the appropriate water treatment features, Saddam [31] examined how the water flow rate and current velocity affected the consistency and compressive strength of concrete. The findings demonstrated that the best increase in concrete compressive strength and workability is attained when the water flow rate and velocity were 0.22 L/s and 0.71 m/s, respectively. The workability and compressive strength of concrete and mortar made from MW and granulated blast furnace slag were examined by Su et al. in [32]. Samples of mortar's compressive strength rose by 9–19%, while that of a concrete sample rose by 10–23%. Using two types of cement, Al-Safy [33] investigated the impact of MW on the workability and compressive strength of concrete and found that MW may increase concrete workability by 69% and 13.7%, respectively, when using standard Portland cement and rapid hardening Portland cement. When utilizing MW, concrete slump increased by 90%, according to research by Mohammadnezhad et al. [34], since MW clusters contain fewer water molecules.

As per the above literature, no studies explored the impact of using MK and MW on concrete characteristics. Concrete that combines MK and MW can provide a product that is less detrimental to the environment and has less cement production and CO_2 emissions. Additionally, the magnetization technique still requires improvement for use in concrete applications. The goal of this investigation is to evaluate the mechanical characteristics of concrete containing MK and MW. In the first stage of this study, the effect of a variety ratios of MK on concrete workability, compressive strength, tensile strength, and flexural strength was studied using TW as the concrete mixing water. In the second stage, the best MK ratio from the first stage was chosen to study the effect of the water magnetization method on concrete properties and to determine the best water magnetization method. Scanning electronic microscope (SEM) analysis was also carried out on selected mixes to closely investigate the effect of MK and MW on concrete microstructure. Figure 2 shows the scenario followed to produce sustainable concrete in this study.

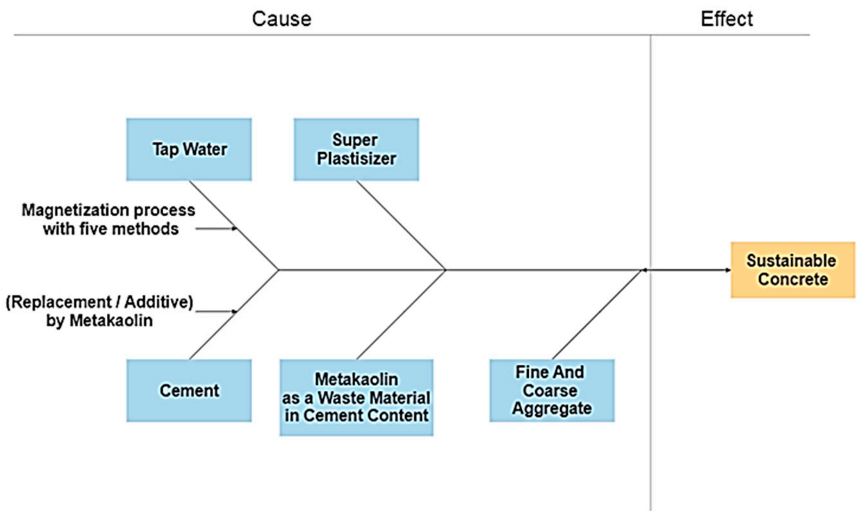


Figure 2. Ishikawa cause-and-effect diagram of producing sustainable concrete utilizing metakaolin and magnetized water.

2. Experimental Research Program

2.1. Materials

Cement: All mixes contained ordinary Portland cement (OPC) (52.5 N), which had a specific gravity of 3.14 and complies with Egyptian Standards ES 2421:2009 [35]. The chemical composition of the cement used is presented in Table 1.

Table 1. Chemical composition of OPC.

Element	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	LOI
OPC	62.70	20.20	6.00	3.30	2.00	2.20	0.01	1.70

Aggregate: The 5 mm siliceous natural sand utilized in this investigation had a water absorption of 0.8% and a specific gravity of 2.62. The dolomite utilized had a nominal maximum size of 12.6 mm, a water content of 1.26%, and a specific gravity of 2.62.

Superplasticizer: an organic polymer Sikament 163 superplasticizer (Type F—brown color) produced by SIKA CO (Bar, Switzerland) was used. It had a specific gravity of 1.08 and was used at a ratio of 1.5% of cement weight. Other superplasticizer ratios of 0.5%, 1%, and 2% have been examined in trial mixes and the ratio of 1.5% showed the best concrete workability. The use of sikament 163 at a ratio of 1.5 % was supported by [36].

Metakaolin: In all mixes in this investigation, MK with a specific gravity of 2.25 that complies with Egyptian Standards 4756-1/2013 [37] was employed as a cement addition and a cement partial replacement. Table 2 shows the chemical composition of MK.

Table 2. Chemical composition of MK.

Element	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	P_2O_5	LOI
MK	0.29	62.07	24.31	1.72	0.27	0.01	0.01	0.65	0.02	8.98

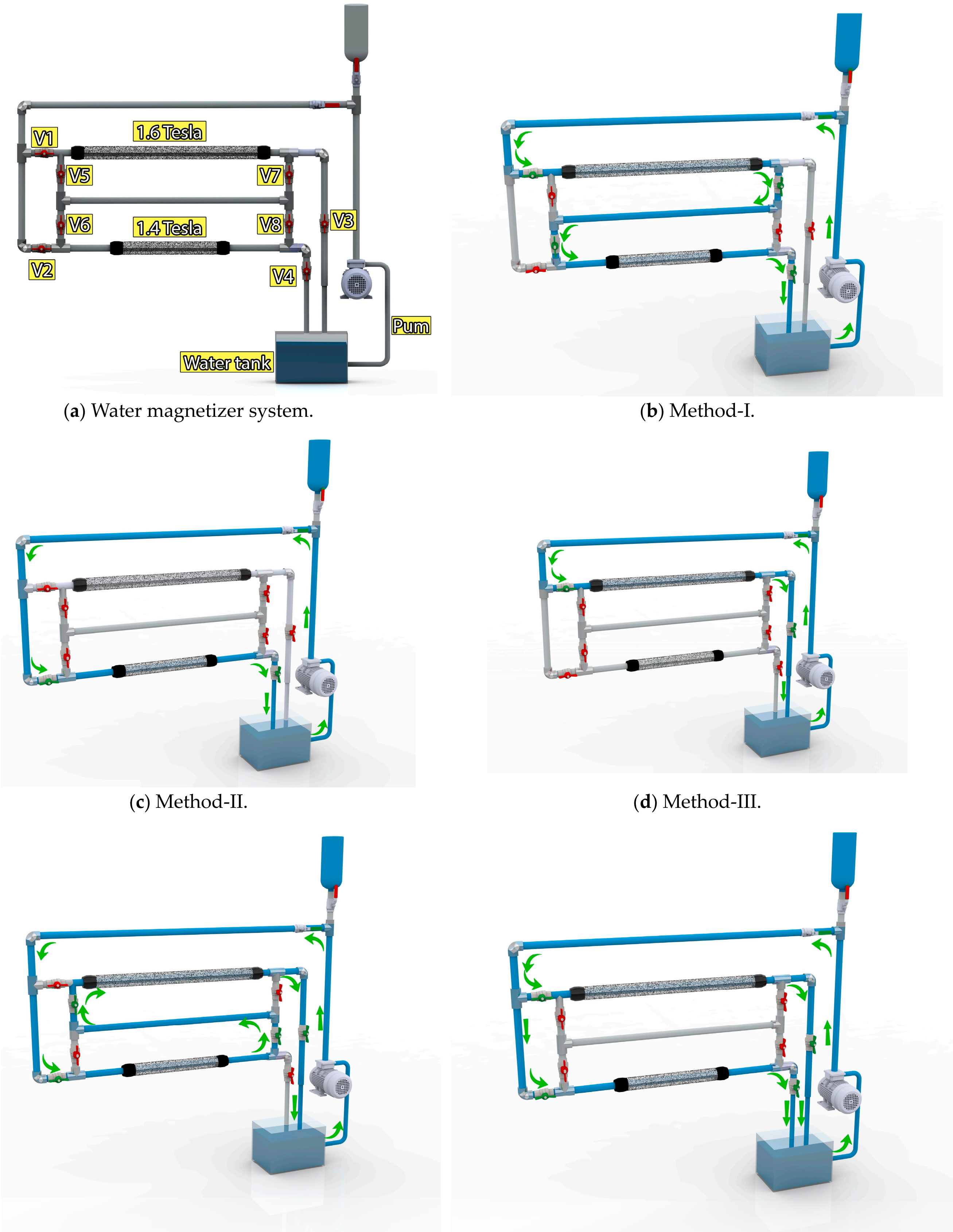
Water: The two types of water used in this investigation were MW and ordinary TW. The MW was made by passing normal TW for 150 cycles through two permanent magnets with 1.6 and 1.4 Tesla intensities using different methods. The number of cycles was selected based on the recommendations of earlier research [30,38]. Figure 3 shows the water magnetization system used in this study.

Five different methods (M-I, M-II, M-III, M-IV, and M-V) for water magnetization have been presented and assessed in order to determine how the magnetization process affects the properties of concrete; see Figure 3. These methods were adaptable based on the direction of the water flow via a group of pipes and the strength of the magnetic fields. A number of eight valves were utilized to control the water flow during each method. Table 3 shows the details of each water magnetization method and the open/closed valves in each one.

Table 3. Details of water magnetization methods.

Magnetization Method	Water Direction	Valves System							
		V1	V2	V3	V4	V5	V6	V7	V8
M-I	Series of pipes (Upper to lower)	O	C	C	O	C	O	O	C
M-II	Only Lower	C	O	--	O	--	C	--	C
M-III	Only Upper	O	C	O	--	C	--	C	--
M-IV	Series of pipes (Lower to Upper)	C	O	O	C	O	C	C	O
M-V	Parallel pipes	O	O	O	O	C	C	C	C

O: Open. C: Closed.



(**a**) Water magnetizer system. (**b**) Method-I.

(**c**) Method-II. (**d**) Method-III.

(**e**) Method-IV. (**f**) Method-V.

Figure 3. Water magnetization system and methods used.

2.2. Mixes and Variables

Seven ratios of MK, namely 0%, 5%, 10%, 20%, +5%, +10%, and +20%, were used as a partial cement replacement or as an additive to cement. Five water magnetization methods, namely M-I, M-II, M-III, M-IV, and M-V, were also employed in this experiment.

The experimental program consisted of twelve concrete mixes divided into two groups. The first group included seven mixes and investigated the impact of various MK ratios on the performance of concrete mixed with TW. The second group included five mixes, one per each magnetization method, and carried out on a selected mix from the first group. Table 4 displays the details of all mixes in this study. All mixes had a constant water to binder ratio of 0.35, a constant content of cementitious material of 500 kg/m^3, and a constant superplasticizer dosage of 1.5% of the total cementitious materials weight. The coarse to fine aggregate ratio of 2.0 was constant for all mixes. As shown in Table 4 (Group-1), due to the difference in the specific gravities between cement and MK, and to compromise that difference with maintaining the 1 m^3 mix volume, a limited change has been conducted in the coarse aggregate so that the MK content was the main variable to affect the measured concrete properties.

Table 4. Information of concrete mixes in the experiment.

Group	Mix Code	Coarse Aggregate kg/m^3	Fine Aggregate kg/m^3	Cement		MK		TW kg/m^3	MW kg/m^3	SP kg/m^3
				%	kg/m^3	%	kg/m^3			
1	MK0TW	1179	589	100%	500	0%	0	175	-	7.5
	MK5TW	1176	588	95%	475	5%	25	175	-	7.5
	MK10TW	1174	587	90%	450	10%	50	175	-	7.5
	MK20TW	1169	585	80%	400	20%	100	175	-	7.5
	MK+5TW	1148	574	100%	500	+5%	25	175	-	7.5
	MK+10TW	1114	557	100%	500	+10%	50	175	-	7.5
	MK+20TW	1048	524	100%	500	+20%	100	175	-	7.5
2	MK+10-I	1114	557	100%	500	+10%	50	-	175	7.5
	MK+10-II	1114	557	100%	500	+10%	50	-	175	7.5
	MK+10-III	1114	557	100%	500	+10%	50	-	175	7.5
	MK+10-IV	1114	557	100%	500	+10%	50	-	175	7.5
	MK+10-V	1114	557	100%	500	+10%	50	-	175	7.5

MK: metakaolin; TW: tap water; MW: magnetized water; SP: superplasticizer.

The mix ID in Table 4 explains the components and method used in each mix. For example, in the first group, mix MK5TW means it had 5% MK as partial cement replacement and was made with TW, while mix MK+5TW means it had 5% MK as additive to the cement and was made with TW. In the second group, mix MK+10-III means it had 10% MK as additive to cement and was made with MW that was magnetized using method M-III.

The coarse and fine aggregates were first added to the mixer, then cement was added and blended for two minutes. MK was then added and followed by the addition of water (TW or MW) and superplasticizer, which were all thoroughly mixed. The concrete was then cast into 100 × 100 × 100 mm cubes for measuring compressive strength at 7, 28 and 365 days, 100 × 200 mm cylinders for measuring splitting tensile strength at 28 days, and 100 × 100 × 750 mm beams for measuring flexural strength at 28 days. After 24 h, the specimens were demolded, cured in lime-saturated water.

2.3. Methods of Tests

2.3.1. Workability Evaluation

The workability of the mixtures has been assessed using the slump test. The cone-shaped slump test mold had dimensions of 200 mm at the bottom, 100 mm at the top, and 300 mm high. Three layers of concrete have been poured from the smaller entryway, which is located at the top and was supported by a smooth surface. A typical 16 mm diameter steel rod was used to compact each layer 25 times, in compliance with ASTM C 143–10: 2015 [39].

2.3.2. The Compressive Strength Test

The compressive strength of the concrete was measured using a load-controlled hydraulic jack that had a 2000 KN capacity and was loaded at a rate of 0.2 to 0.4 N/mm^2 per second. The specimens were exactly centered inside the equipment to avoid measuring errors. The loading was then manually set until the compressive measurement of the manometer reached its maximum degree of stress. The compression test was performed in accordance with BS EN 12390-4 [40]. At 7, 28, and 365 days following the casting date, the specimens were tested. The average ultimate compressive stress of three specimens per mix was used to determine the compressive strength of each mix.

2.3.3. The Splitting Tensile Strength Test

The splitting tensile test was used to determine the tensile strength of concrete in this study. The longitudinal direction of the cylindrical specimen (100 mm in diameter and 200 mm in height) was subjected to compressive force. Three specimens per mix were tested according to [41].

2.3.4. SEM Analysis

The cracked surfaces of the concrete test specimens have been gold plated to enhance resolution and lower electric charge. The material's electron states would be altered by a high intensity electron beam striking it, adding secondary and backscattered electrons. For a specific incident voltage, the specimen's surface emits electrons depending on the surface feature. The scanning electron microscope uses these electrons to draw an image of the surface. The concrete samples were scanned with a JEOL (Akishima, Tokey) JSM 6510 lv microscope (Electron Microscopy Unit, Mansoura University, Mansoura, Egypt) at an acceleration voltage of 30 kV.

3. Results and Discussions

3.1. Workability

The slump test has been used to evaluate the workability of MK concrete. The cone-shaped slump test with dimensions of 300 mm high, 100 mm in diameter at its top, and 200 mm in diameter at its bottom was used to measure concrete workability according to ASTM C 143-10: 2015 [42]. Figure 4 presents the slump test result of MK concrete mixed with TW. As shown, adding more MK to concrete as a cement substitute or as additional cementitious material reduced concrete workability by 2–8%. Concrete slump decreased by 2%, 3%, 5%, 6%, and 8% when 5%, 10%, 20%, +5%, +10%, and +20% MK were used, respectively. Because of MK's high fineness and relatively tiny size, which allow it to absorb into the mixing water, concrete slump decreased as MK concentration increased. [28]. In addition, MK features polygonal particles with sharp edges in contrast to cement's rounded particles, which contributed toward the concrete slump decrease [21].

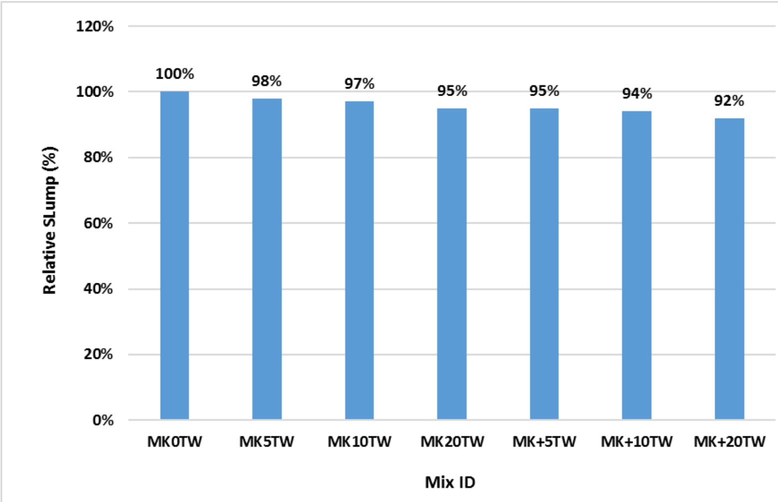


Figure 4. Impact of different ratios of MK on the slump values of concrete mixed with TW.

3.2. Mechanical Properties

3.2.1. Compressive Strength

Figure 5 illustrates the effect of utilizing different amounts of MK on the concrete's compressive strengths at 7, 28, and 365 days (Group-1 mixes). When used as a replacement of cement or additive at the age of 7 days, 5% MK reduced the compressive strength by around 9%. Compressive strength losses were recovered when the MK content was increased beyond 5%. Mix MK10TW displayed the compressive strength as that of the control mix MK0TW. The strength increased by 8% in mix MK20TW compared to the control mix MK0TW as the MK content was increased to 20%. Using MK as a cement additive displayed different effects from those occurred when used as cement replacement. The compressive strength increased by 10% when MK was used as a cement additive with a 10% content; however, when the MK content was 5% or 20% in mixes MK+5TW and MK + 20TW, it decreased by 10% and 13%, respectively. With the exception of mix MK+20TW, where the 28-day compressive strength decreased by 14%, utilizing MK as a cement replacement or additive increased compressive strength by up to 14%. The use of MK as a cement replacement or additive had a varying impact on the concrete's compressive strength at 365 days, with up to a 12% strength improvement being noted in mix MK10+TW.

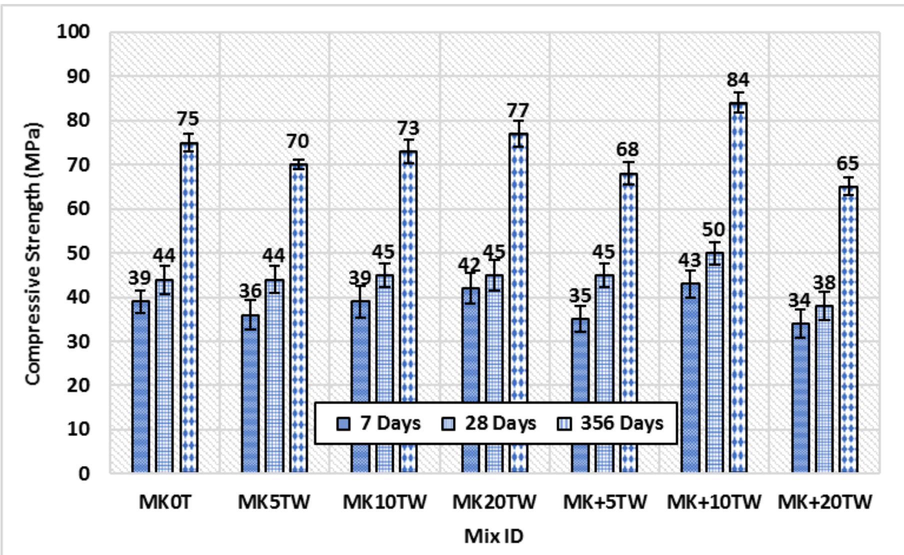


Figure 5. Effect of ratios of MK on the compressive strength of concrete mixed by TW (reprinted from [21]).

Based on the previously mentioned results, it may be deduced that MK can have positive impacts on concrete at later ages of 28 and 365 days, especially if added to cement at a 10% content. The reaction between MK and the calcium hydroxide produced from the cement process of hydration and the creation of calcium silicate hydrate (C-S-H) gel was responsible for the strength improvement. Concrete's compressive strength increased as C-S-H gel composition was increased [43,44].

3.2.2. Splitting Tensile Strength and Flexural Strength

Results for the 28-day splitting tensile strength and flexural strength of concrete prepared with TW (group-1) are shown in Figures 6 and 7, respectively. The results of splitting tensile strength and flexural strength followed the same pattern as those for compressive strength. The concrete splitting tensile strength enhanced by 3%, 11%, and 11%, respectively, when concrete cement was partially replaced by MK with 5%, 10%, and 20% (Figure 6), and the corresponding flexural strength increased by 6%, 9%, and 5%, respectively (Figure 7). The splitting tensile strength of concrete increased by 12%, 18%, and 9%, respectively, when MK was added to cement in amounts of 5%, 10%, and 20% (Figure 6), while the corresponding flexural strength increased by 13%, 17%, and 11%, respectively (Figure 7). Due to its smaller particle size compared to cement, MK has a filling effect that is able to increase tensile and flexural strengths. It also reacts with cement to form C-S-H, which strengthens the bond within the concrete matrix and increases the tensile and flexural strengths.

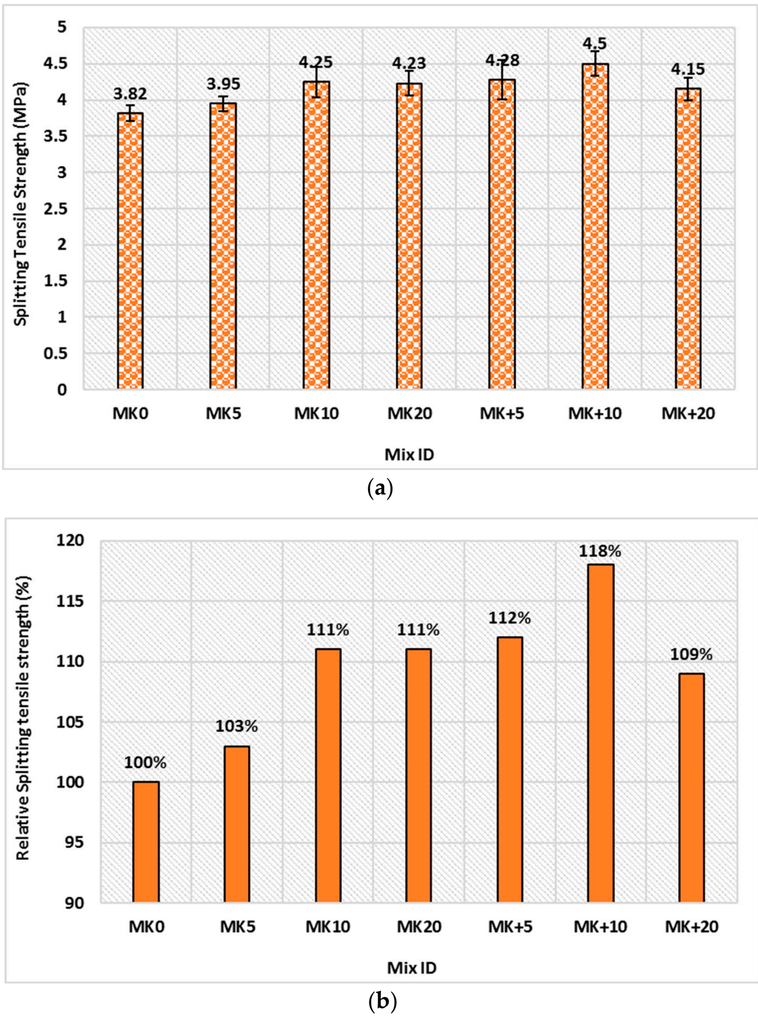
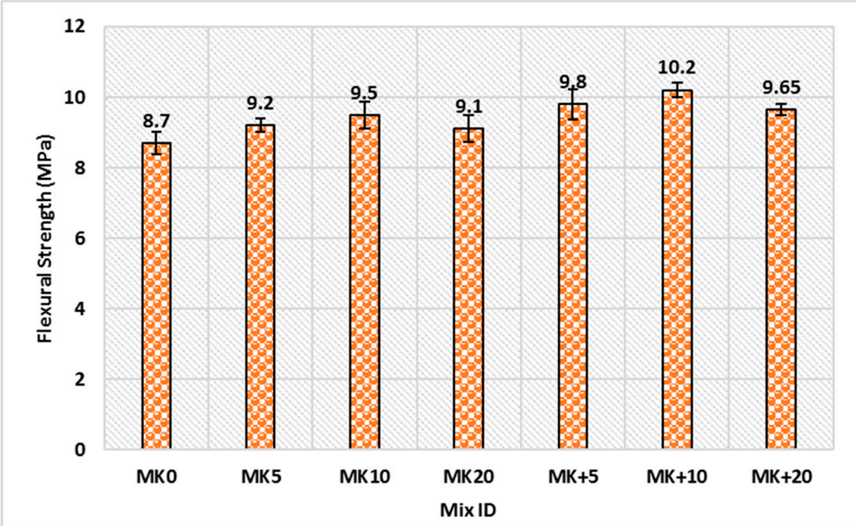
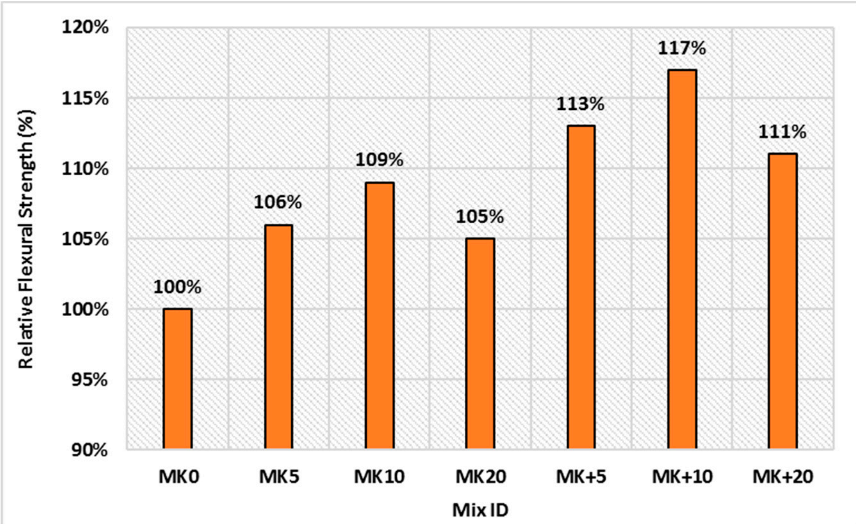


Figure 6. Variation in 28-day splitting tensile strength for MK concrete made with TW: (**a**) values with error bars, and (**b**) relative change.



(**a**)



(**b**)

Figure 7. Variation in 28-day flexural strength for MK concrete made with TW: (**a**) values with error bars, and (**b**) relative change.

3.3. Effect of the Water Magnetization Method

The effect of the water magnetization method was measured on a selected mix from Group-1, namely MK+10, that showed the best performance when prepared with TW. Five different magnetization methods were applied on this mix as shown in Group-2; see Table 2. For Group-2 mixes, concrete workability and compressive strength at 7, 28, 365 days were measured and compared. Figure 8 displays the slump values for the concrete mixes of Group-2. As shown in Figure 8, the water magnetization method did not have significant effect on MK concrete slump. Compared with magnetization method M-I, all other methods showed 1% less slump. The effect of slump values after using MW, especially method M-I, showed that this method enhanced concrete workability by up to 2%. The insensitivity of MK concrete workability with changing the magnetization methods is attributed to the ability of MW to disperse more cement particles during the hydration process, this enhanced the hydration process, and hence the workability.

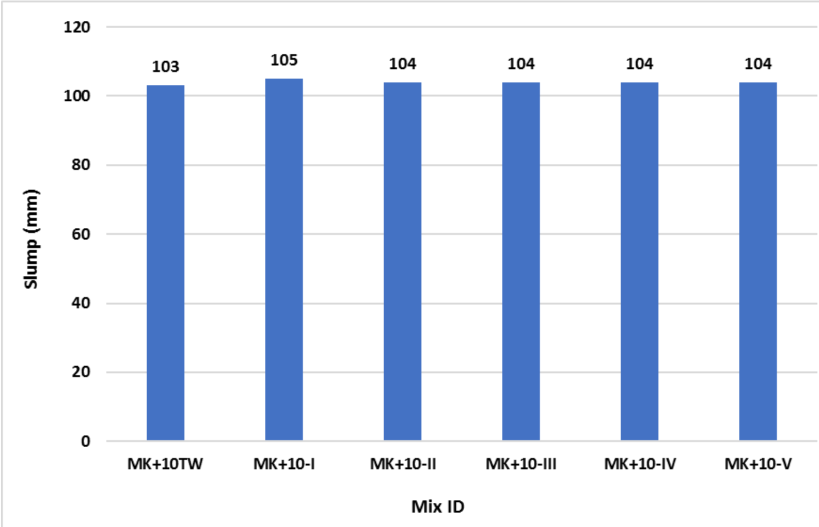


Figure 8. Effect of different methods of water magnetization on MK concrete slump.

Figure 9 presents the results of the compressive strength for the concrete mixes of Group-2. Using magnetization method M-I enhanced concrete compressive strength by 21%, 16%, and 18% at 7, 28, and 365 days. Compared with magnetization method M-I, all other method showed obvious reduction in MK concrete compressive strength by up to 15% at 7 days, 14% at 28 days, and 16% at 356 days. The momentum of water from the upper device of magnetization to the lower device, that doubles the magnetic field intensity, was associated with the effectiveness of magnetization method M-I. As a result, cement particles developed a soft layer of hydration reaction products on top of them, preventing water molecules from reaching the material bulk.

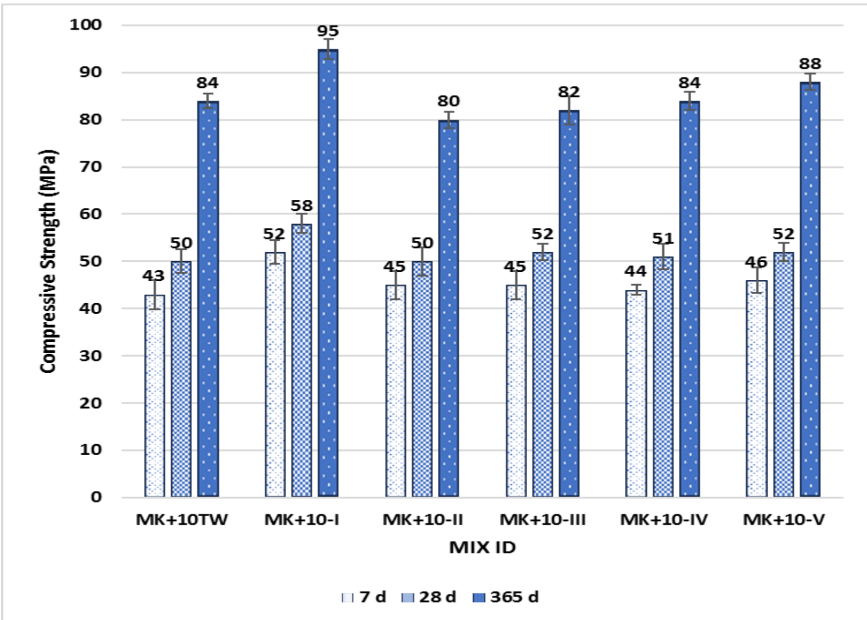
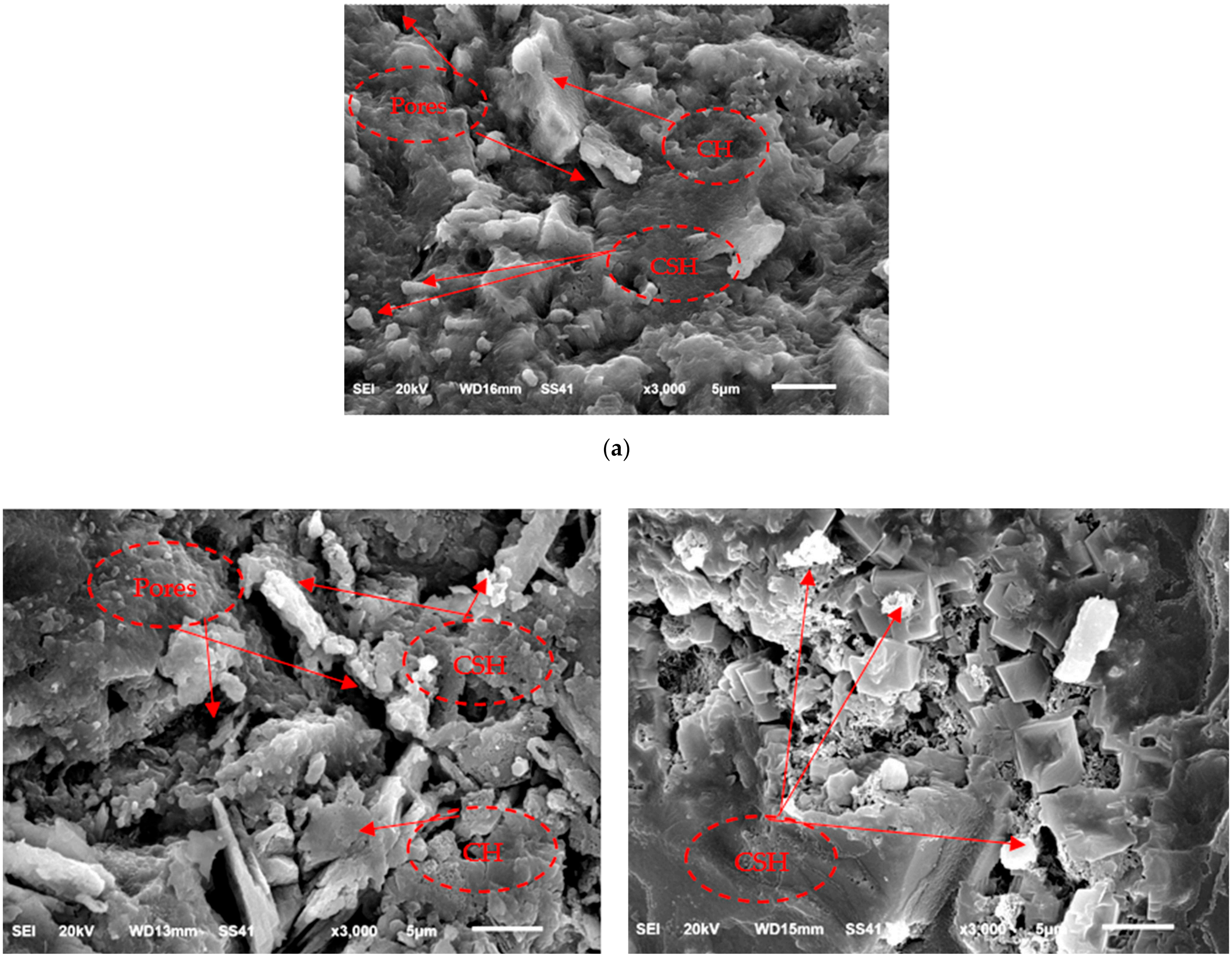


Figure 9. Effect of different methods of water magnetization on MK concrete compressive strength.

3.4. SEM Analysis

SEM analysis was carried out on concrete samples taken from tested specimens of mixes MK0TW, MK+10TW, and MK+10-I to closely investigate the combined effect of MK and MW on concrete microstructure. Figure 10 presents the SEM images of the scanned samples. As shown in the figure, the extent of C-S-H generation, i.e., the extent of the hydration process, is presented in all SEM images with different contents. Figure 10a shows the aggregation of poorly crystalline C-S-H gel particles (mix MK0TW) compared with more intermixed C-S-H gel and other products that are presented in Figure 10b when using 10% MK as a cement additive with TW in mix MK + 10TW. This indicated the effectiveness of MK in enhancing the concrete microstructural properties. The use of MW improved the concrete internally as there was more C-S-H, less calcium hydroxide, and the concrete becomes denser when MW was presented in mix MK+10-I, as shown in Figure 10c. Furthermore, significant crystals can be observed in the concrete mixes with MK and MW compared to other mixes. This decreased the cracks and pores in the concrete matrix, and hence increased the compressive strength. The combination of MK and MW in mix MK+10-I (Figure 10c) showed remarkable microstructural shape among other scanned mixes as it showed relatively dense concrete with high degree of homogenization between its components. This revealed the enhancements reported in the mechanical properties of mix MK+10M.



(**a**)

(**b**) (**c**)

Figure 10. SEM analysis for mixes: (**a**) MK0TW, (**b**) MK + 10TW, and (**c**) MK + 10-I.

4. Conclusions

In this work, seven mixes (stage-1) were used to evaluate the effect of different ratios of MK on the workability and mechanical properties of metakaolin concrete (MK) prepared with tap water (TW). After that, the best mix of concrete from stage-1 was mixed with magnetized water (MW) prepared with five different magnetization methods (stage-2).

The following are the key conclusions of this study (conclusions 1–4 from stage-1 and conclusions 5–6 from stage-2):

1. Mix MK+10TW showed the best results of the mechanical properties in this study. This mix included 10% of MK added to cement in concrete.
2. The slump results of mixes prepared with MK and TW showed a decrease in values of slump by up to 8% due to the comparatively small size, high fineness, and polygonal particle shape of MK, which make it absorbable to the mixing water.
3. Adding 10% of MK (mix MK+10TW) to concrete enhanced the compressive strength of concrete by up to 10%, 14%, and 12% after 7, 28, and 365 days compared to the control mix MK0TW.
4. The splitting tensile strength of MK+10TW mix enhanced by 18% and the flexural strength of MK+10TW mix enhanced by 17%, compared to the control mix MK0TW.
5. The best method of water magnetization was "method M-I" that had the water flow passing through 1.6 T permeant magnet and then 1.4 T permeant magnet sequentially for 150 cycles. The slump value of mixes prepared with this method was enhanced by up to 2%. The compressive strength results also increased by up to 21%, 16%, and 18% after 7, 28, and 365 days.
6. SEM analysis showed that 10% MK as a cement additive was able to form a more intermixed C-S-H gel, compared with no MK in concrete made with TW. The use of MW in mix MK+10-I improved the concrete internally as there was more C-S-H, less calcium hydroxide, and the concrete became denser, compared with mix MK+10TW.

Overall, using magnetized water in metakaolin concrete enhanced its mechanical and microstructural characteristics, which can be recommended for producing large-scale concrete structures. It is recommended for future studies to employ magnetized water (with the best magnetization method found in this study) in different types of concrete such as self-compacting concrete, volcanic concrete, rubberized concrete, and lightweight concrete. In addition, a techno-economical study is needed to study the feasibility of magnetized water in concrete.

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