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# Characteristics of Sustainable Concrete Containing Metakaolin and Magnetized Water

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**Abstract:** In this study, fourteen sustainable concrete mixes containing metakaolin (MK) as supplementary cement material (SCM) and magnetized water (MW) as concrete mixing water were designed, prepared, tested, analyzed, and compared. The MK was used as a partial replacement of cement weight by 5%, 10%, and 20%, and as an additive to cement by 5%, 10%, and 20% of cement weight. The MW was used to fully replace tap water (TW) in concrete mixes and was prepared using two different magnetic fields of 1.4 tesla (T) and 1.6 T. This experimental research aimed to assess the characteristics of concrete manufactured with MK and MW. The mechanical and durability characteristics of fresh and hardened concrete were measured for the assessment. Microstructural and chemical analyses were carried out on selected materials and concrete mixes. The workability and compressive strength of the materials at 7, 28, and 365 days were measured, in addition to the splitting tensile strength at 28 days and the flexural strength at 28 days. The compressive strength at 365 days was conducted at 18 °C and 100 °C to study the effect of the applied variables on the concrete durability at different elevated temperatures. The microstructural and chemical analyses were conducted using a scanning electron microscope (SEM), energy dispersive X-ray (EDX), and Fourier transform infrared (FTIR) spectroscopy. The results showed that using 10% MK as a cement additive was the best ratio in this study, which enhanced all the measured mechanical characteristics when the TW or MW was used. Using MW instead of TW in MK concrete increased all the mechanical properties measured at 28 days by about 32–35%. The results of the microstructural and chemical analyses supported the compressive strength increase by showing indications of more C-S-H gel production and less CH when using MW in MK concrete. In addition, fewer micro-cracks and pores, and relatively denser concrete, were detected when using MW with 10% MK as a cement additive.

**Keywords:** metakaolin; magnetized water; sustainable concrete; mechanical characteristics; microstructural and chemical analyses

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## 1. Introduction

Cement-based materials are the most widely utilized materials in the construction industry due to their low cost and high strength [1]. However, the formation of cracks, existing pores, low tensile strength, and strain capacities of cement-based materials are the drawbacks that decrease their mechanical characteristics and durability [2,3]. Most of the recent research is focused on controlling the cracks and pores using different types of fibers and concrete materials [4–7]. Recently, because of their benefits, supplementary cement materials (SCMs) were taken into consideration. The benefits of SCMs include the formation of extra calcium silicate hydrate (C-S-H), the consumption of unfavorable calcium hydroxide (CH) in concrete, the reduction of concrete permeability, and the reduction of

cement use and its $CO_2$ emissions during manufacturing [8,9]. The building of infrastructure with a long-term service life is required for longer-serviced cement products, which will minimize the application of cement in the concrete sector [10]. There are several types of SCMs that have been developed up to date, including metakaolin (MK), mechanically activated kaolin, flash calcined clay, and calcined clay. Of these materials, metakaolin has attracted researchers' interest because of its technological and financial advantages [11,12]. Metakaolin is formed by exposing calcining kaolin to high temperatures and typically contains 40–45% aluminum oxide ($Al_2O_3$) and 50–55% silicon dioxide ($SiO_2$) [13]. The byproduct of cement hydration processes, CH, adversely affects the concrete's mechanical and durability properties and does not significantly contribute to the desired strength [14]. The $SiO_2$ and $Al_2O_3$ that are in MK can react with CH to create C-S-H, calcium aluminate hydrates (CAH), and calcium alumino-silicate hydrates (CASH) when water is present in concrete [14,15]. Employing 20–40% MK in concrete removes CH after 28 days of concrete age, according to the work done by [16,17]. Using MK in concrete reduces CH by 83% after 28 days of concrete age, according to [18].

Few research has been carried out on utilizing MK in concrete. Rashad [19] studied the effect of using MK on concrete workability and reported a negative effect on concrete workability. Employing MK in concrete made with recycled coarse aggregate caused a slight reduction in its workability [20]. Chu and Kwan [21] studied the effect of different MK ratios on the fresh properties of mortar and found that adding 20% MK to cement mortar with varying water-to-cementitious-material ratios marginally improved the mortar's fresh properties. They related these improvements to the MK's superior filling effect and dense packing. The effect of MK on concrete tensile strength and modulus of elasticity was measured by [22,23], and they found that 20% MK in concrete improved its tensile strength and dynamic modulus of elasticity. Al Menhosh et al. [24] mentioned that the use of 15% MK with 5% polymer in concrete increased its flexural and tensile strengths by up to 15% with no significant effect on compressive strength after 180 days. Jiang et al. [25] used 6% and 10% MK in mortar made with 2% steel fiber and observed an improvement in its flexural toughness. Rashiddadash et al. [26] studied the effect of using MK and pumice powder on the concrete mechanical properties and reported that the combination of 7.5% pumice and 7.5% MK together is better than using 15% pumice for increasing all the mechanical properties of hybrid fiber-reinforced concrete.

Using magnetically treated water in cementitious composites is a simple, cost-effective, and environmentally responsible technique to enhance their characteristics [27,28]. Magnetized water (MW) is regular tap water (TW) that is passed through a magnetic field with a specific intensity. The physicochemical characteristics of water could be changed by this magnetization type of treatment [29]. Water magnetization plays a significant role in dispersing the water molecules and hence, improving the cement hydration reaction, as shown in Figure 1. Relatively small molecules of MW help in easily penetrating the cement particles [30].

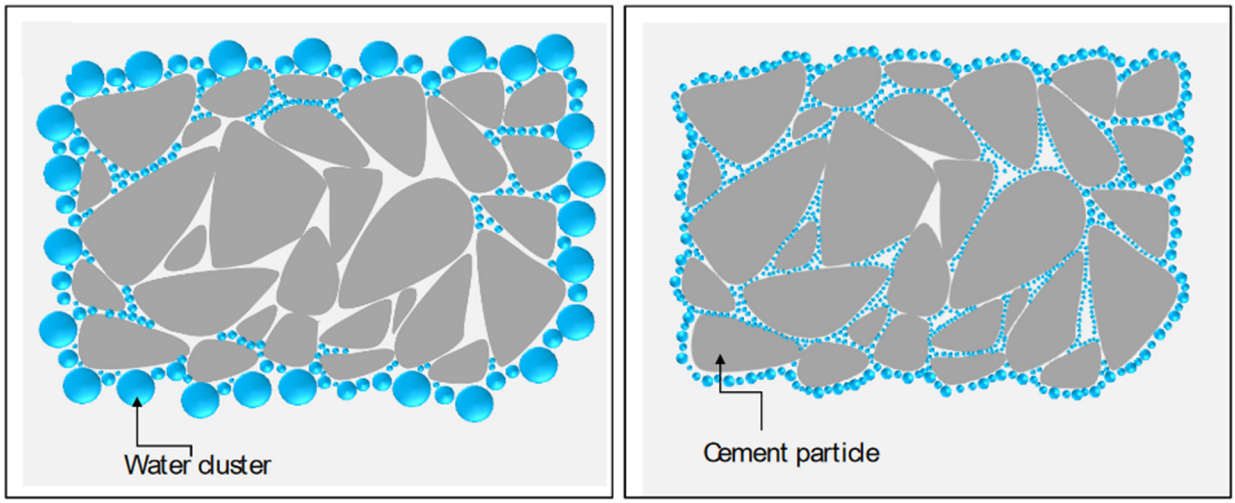



**Figure 1.** Penetration of cement particles by (**a**) TW and (**b**) MW [31].

According to previous studies, the bond angles of the water molecules decreased as a result of water magnetization, falling from 105 to 103 [32], and the specific boiling point of the water dropped from 99.2 °C to 97.2 °C; however, the water's viscosity increased by 10% [33,34]. By magnetizing the water, its electrical conductivity increases from 56 ms/cm to 264 ms/cm [28]. Al-Safy [35] studied the effect of using MW on the workability and compressive strength of concrete by using two types of cement and reported that MW could improve concrete workability by 69% and 13.7% when using regular Portland cement and rapid hardening Portland cement, respectively. In addition, MW improved the concrete compressive strength in which the concrete cement content can be decreased by 16% to maintain the same strength, similar to that of concrete made with TW. This can indicate a reduction in cement usage. Mohammadnezhad et al. [31] studied the effect of MW on concrete slumps and reported a 90% increase in concrete slumps when using MW due to the MW clusters that have fewer water molecules. Keshta et al. [36] conducted an experimental study on using MW and volcanic ash to produce sustainable concrete and reported that using the MW, prepared with an intensity of 1.4 tesla (T) in addition to volcanic ash, improved the mechanical properties of volcanic concrete up to 35%. Keshta et al., in another study [37], measured the effect of different magnetic fields on the compressive strength of concrete and reported that using different intensities of the magnetic field in preparing the MW positively affected the compressive strength of the concrete. ELShami et al. [38] carried out a study on producing self-compacted concrete by using MW and reported that self-compacted concrete properties could be enhanced by using MW prepared with a magnetic field intensity of 1.4 T.

Water magnetization increases the water specific area, which positively affects the mechanical properties of concrete (such as compressive, flexural, and tensile strengths) [31]. Reddy et al. [39] evaluated the effect of MW on the compressive strength of concrete using spherical magnets while varying the exposure time to a magnetic field. The results showed that the compressive strength was unsatisfactory when magnetizing the water for up to five hours, however, the results reported at the six-hour magnetization time were more pronounced. Increasing the magnetization time by more than 24 h was not advisable. Moreover, a notable increase in the concrete compressive strength was reported when the water was magnetized with both the north and south poles compared with water magnetized using either the north or south poles individually.

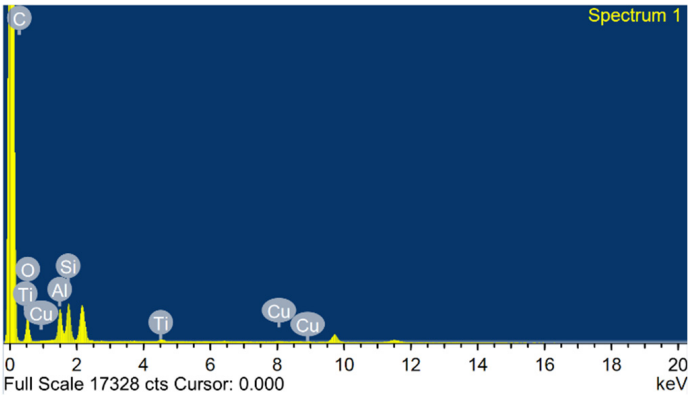
As per the literature above, few research works have been carried out on using MK in concrete, especially that made of MW. This experimental study aims to fill the research gap and assess the characteristics of concrete manufactured with MK and MW. A total of

fourteen concrete mixes, including MK with (5%, 10%, and 20%) as cement replacement or cement additive, were tested and compared. The characteristics of fresh and hardened concrete were measured for the assessment. Microstructural and chemical analyses were carried out on selected materials and concrete mixes to closely investigate the effect of the applied materials/variables. Scanning electron microscope (SEM), energy dispersive x-ray (EDX), and Fourier transform infrared (FTIR) spectroscopy were the conducted microstructural and chemical analyses. By combining MK and MW in concrete, it is possible to produce a type of sustainable concrete and reduce the harmful impacts of $CO_2$ emissions.

## 2. Experimental Program

### *2.1. Materials*

Ordinary Portland cement (OPC), with a specific gravity of 3.15 that complies to Egyptian Standards ES 2421:2009 [40], was used in all mixes. MK was used as a cement partial replacement or additive. The specific gravity of MK was 2.25, according to Egyptian Standards 4756-1/2013 [41], and it was analyzed using energy dispersive X-ray (EDX), as shown in Figure 2. As shown, the pozzolanic elements are present, including 6.70% alumina (Al), 9.64% silicon (Si), and 39.36% oxygen (O). Table 1 shows the chemical composition of cement and MK, according to BS EN 12620:2002 [42]. The fine aggregate used in this study was 5 mm siliceous natural sand with a specific gravity of 2.59 and water absorption of 0.8%. Dolomite was used, with a size of 12.5 mm, 2.62 specific gravity, and 1.26% water absorption. A superplasticizer, type F, with 1.2 specific gravity, according to ASTM C 494-92 [43], was used in all the mixes of this study.



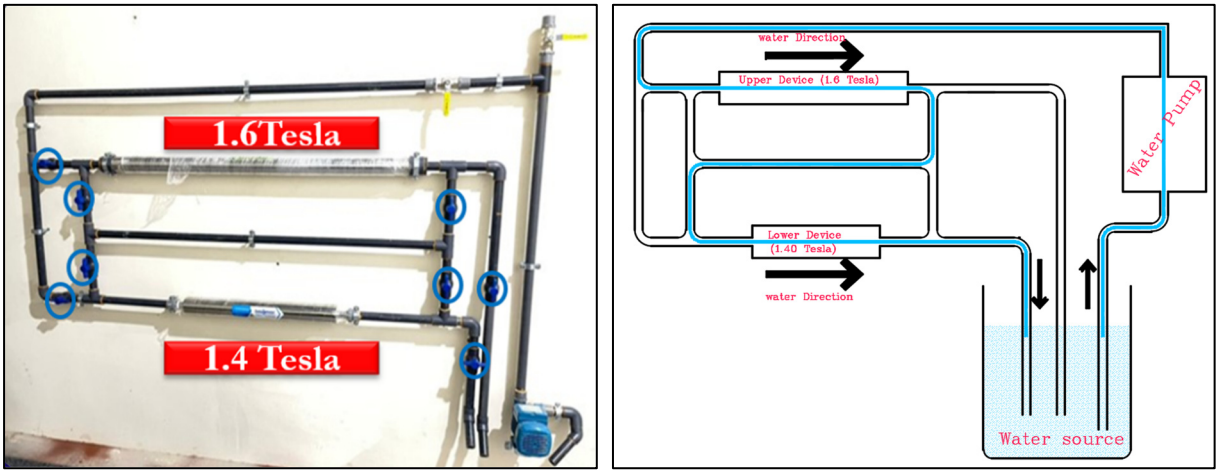

| Element | Weight % | Atomic% |
|---|---|---|
| C | 42.01 | 53.07 |
| O | 39.36 | 37.33 |
| Al | 6.70 | 3.77 |
| Si | 9.64 | 5.21 |
| Ti | 0.92 | 0.29 |
| Cu | 1.38 | 0.33 |

**Figure 2.** EDX analysis of MK.

**Table 1.** Composition of the cementitious materials used.

| Element | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|
| OPC | 62.7 | 20.20 | 6.00 | 3.30 | 2.00 | 2.20 | 0.01 | -- | -- | 1.70 |
| MK | 0.29 | 62.07 | 24.31 | 1.72 | 0.27 | 0.01 | 0.01 | 0.65 | 0.02 | 8.98 |

The water utilized in this investigation was normal TW and MW. The MW was magnetized using two permanent magnets with intensities of 1.4 T and 1.6 T. The method of water magnetization was to pass TW through the 1.6 T magnet first and then through the 1.4 T for 150 cycles. The chosen method of magnetization was selected based on recommendations from previous research [27,37] that compared the efficiencies of several water magnetization methods. This magnetization method was carried out, as explained in Figure 3, using some water tubes, a water pump, a water tank, and some valves. The water pump was used to achieve the required number of cycles for water magnetization. The water valves were used to direct the flow of the water with the designed sequence.




(**a**) (**b**)

**Figure 3.** Water magnetization system: (**a**) real system and (**b**) schematic drawing.

### *2.2. Mixes and Specimens' Preparation*

The concrete mixes of this study were designed according to ASTM C192 (2018) [44] and were divided into two groups with a total number of 14 mixes. Group 1 consisted of 7 mixes made with TW and different ratios of MK as the partial replacement of cement (5%, 10%, 20%) or as an additive to cement (+5%, +10%, +20%). Group 2 consisted of 7 mixes that were typically the same as the mixes in group 1, however, they were made with MW. All mixes have been designed using the absolute volume design method to give the required ingredients for 1 $m^3$ of concrete. The cement has been replaced by weight; however, the volume difference between the cement and metakaolin has been compensated in the mixes by reducing the aggregate content and keeping the fine/coarse aggregate mixing ratio constant. All mixes had a constant superplasticizer content of 7.5 kg/$m^3$ (1.5% of cementitious materials) and a constant water content of 175 kg/$m^3$. Table 2 shows details of each group mix.

**Table 2.** Details of concrete mix designs.

| Group | Mix ID | 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 | K0T | 1179 | 589 | 100% | 500 | 0% | 0 | 175 | - | 7.5 |
| | K5T | 1176 | 588 | 95% | 475 | 5% | 25 | 175 | - | 7.5 |
| | K10T | 1174 | 587 | 90% | 450 | 10% | 50 | 175 | - | 7.5 |
| | K20T | 1169 | 585 | 80% | 400 | 20% | 100 | 175 | - | 7.5 |
| | K + 5T | 1148 | 574 | 100% | 500 | +5% | 25 | 175 | - | 7.5 |
| | K + 10T | 1114 | 557 | 100% | 500 | +10% | 50 | 175 | - | 7.5 |
| | K + 20T | 1048 | 524 | 100% | 500 | +20% | 100 | 175 | - | 7.5 |
| 2 | K0M | 1179 | 589 | 100% | 500 | 0% | 0 | - | 175 | 7.5 |
| | K5M | 1176 | 588 | 95% | 475 | 5% | 25 | - | 175 | 7.5 |
| | K10M | 1174 | 587 | 90% | 450 | 10% | 50 | - | 175 | 7.5 |
| | K20M | 1169 | 585 | 80% | 400 | 20% | 100 | - | 175 | 7.5 |
| | K + 5M | 1148 | 574 | 100% | 500 | +5% | 25 | - | 175 | 7.5 |
| | K + 10M | 1114 | 557 | 100% | 500 | +10% | 50 | - | 175 | 7.5 |
| | K + 20M | 1048 | 524 | 100% | 500 | +20% | 100 | - | 175 | 7.5 |

MK: Metakaolin. TW: Tap water. MW: Magnetized water. SP: Superplasticizer.

All concrete mixes were mixed in a pan mixer with a 60 L capacity. The mixing procedure started by mixing dry cement, coarse aggregate, fine aggregate, and MK, if any, for two minutes. Half of the water was then added and mixed for another two minutes. The superplasticizer, in addition to the other half of the water, was then added

and mixed for the final three minutes. In the mixes incorporating MW, the water was added right away after completing its magnetization. After completing the concrete mixing, the slump test was performed as per ASTM C143 [45]. From each mix, nine cubes of 100 mm (three cubes per measure) were prepared to evaluate the compressive strength at 7 days, 28 days, and 365 days at room temperature (18 °C). Additional three cubic specimens (100 × 100 × 100 mm) were cast from each mix to evaluate the compressive strength at 365 days after the exposure to a relatively high temperature of 100 °C. Two 100 × 200 mm cylinder specimens and two 100 × 100 × 500 mm beams were also cast from each mix to evaluate the 28 day's tensile and flexural strengths, respectively. After being cast for 24 h, the specimens were demolded and allowed to cure in a water bath until the testing day.

### *2.3. Test Techniques and Procedures*

#### 2.3.1. Concrete Workability

The slump cone test was carried out to measure the workability of the proposed mixes in accordance with ASTM C 143-10: 2015 [45]. The slump cone had dimensions of 300 mm in height, 200 mm in lower diameter, and 100 mm in upper diameter. The cone was placed on a flat surface, and three layers of concrete were poured inside the cone. Each layer was compacted 25 times using a 16 mm-diameter standard steel rod. The cone was then gradually lifted, causing the concrete to slump, and hence, the slump was measured.

#### 2.3.2. Concrete Mechanical Characteristics

The compressive strength of the concrete at 7 days, 28 days, and 365 days was measured using a 1900 kN capacity testing machine by testing three 100 mm cubes per measure with a loading rate of 20 MPa/min. At 365 days, another three 100 mm cube specimens from each mix were exposed to the relatively high temperature of 100 °C for 8 h in an electric oven of 250 °C capacity, as shown in Figure 4, and then the compressive strength of those specimens was measured. Two cylinders of 100 × 200 mm per mix were tested to determine the splitting tensile strength at 28 days, with a loading rate of 1.5 MPa/min, using a 1900 kN capacity testing machine. Two concrete prisms of 100 × 100 × 500 mm per mix were tested to determine the flexural strength at 28 days, with a loading rate of 1.0 Mpa/min, using a 300 kN capacity testing machine. The average of the measured hardened concrete characteristics was reported and compared to the corresponding results.




**Figure 4.** Exposing concrete cubes to relatively high temperature at 365 days.

#### 2.3.3. Concrete Microstructure and Chemical Analyses

SEM, EDX, and FTIR analyses were conducted for mixes K0T, K0M, K + 10T, and K + 10M to closely investigate their microstructure and chemical composition. These mixes were selected to carefully examine the effect of MK without the presence of MW in mix K + 10T and the combined effect of MK with MW in mix K + 10M. The results of those

mixes were then compared with the corresponding control mixes (K0T and K0M). In the SEM imaging, the samples taken from hardened concrete were coated by a gold layer of 12 nm, and then using a JEOL JSM 6510 LV microscope, the concrete samples were scanned at a 30 kV acceleration voltage. The EDX analysis was carried out to determine the atomic percentage of each element in the concrete matrix using an Oxford X-Max 20 device. The FTIR analysis was carried out using the Nicolet iS10 device to characterize the concrete organic compounds by knowing the presence of common active groups, knowing the type of bonds that connect the two atoms (whether they are single or double), and knowing the type of protons associated with the carbon atoms (whether they are aliphatic or aromatic).

## 3. Experimental Results and Discussions

### *3.1. Concrete Workability*

Table 3 demonstrates the slump values of the tested concrete mixes. The performance of MK in concrete when using TW (group-1) is shown in Figure 5. As shown, the MK slightly decreased the concrete workability by 2–8%. Using 5%, 10%, 20%, +5%, +10%, and +20% MK in the concrete decreased the concrete slump by 2%, 3%, 5%, 5%, 6%, and 8%, respectively. The slump decrease with the MK content increase is attributed to the relatively small size of MK particles that increase the surface area of the cementitious materials within the concrete matrix, and hence more water is absorbed, and less concrete slump is present.

**Table 3.** Measured concrete slumps for all mixes.

| Group-1 | | Group-2 | |
|---|---|---|---|
| **MIX** | **Slump (mm)** | **MIX** | **Slump (mm)** |
| K0T | 110 | K0M | 113 |
| K5T | 108 | K5M | 110 |
| K10T | 107 | K10M | 108 |
| K20T | 105 | K20M | 107 |
| K + 5T | 105 | K + 5M | 106 |
| K + 10T | 103 | K + 10M | 105 |
| K + 20T | 101 | K + 20M | 103 |

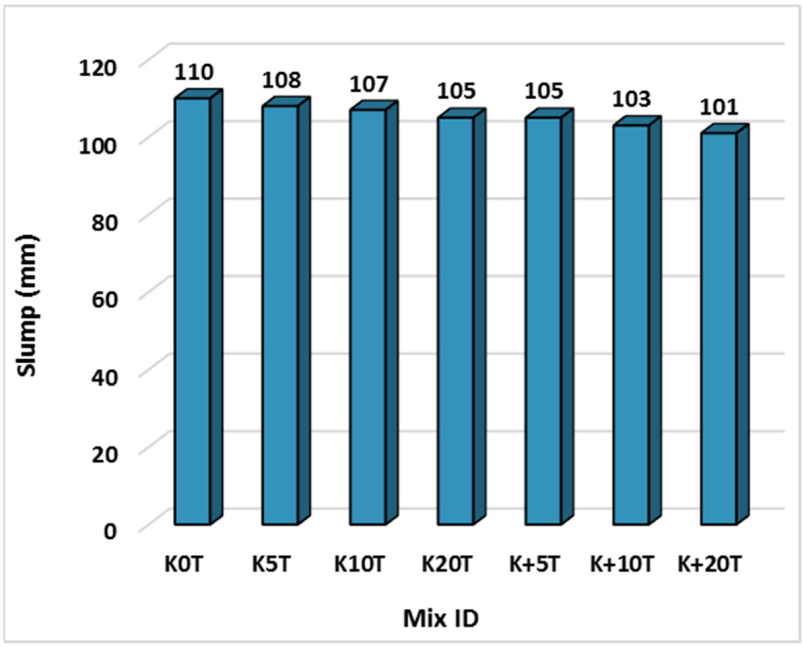



**Figure 5.** The effect of different MK contents on the slumps of concrete mixes produced with TW.

Additionally, MK contains polygonal particles with rough edges, as opposed to cement, which has comparatively round edges [46]. This might adversely affect the ability of MK particles to get wet and increase the frictional resistance of the material. The rough edges of the MK particles are seen in the SEM image in Figure 6. Moreover, there is a strong attraction between MK and cement particles [47] that increases the agglomeration of the cementitious materials in the concrete matrix with the presence of water and hence, decreases the concrete workability.

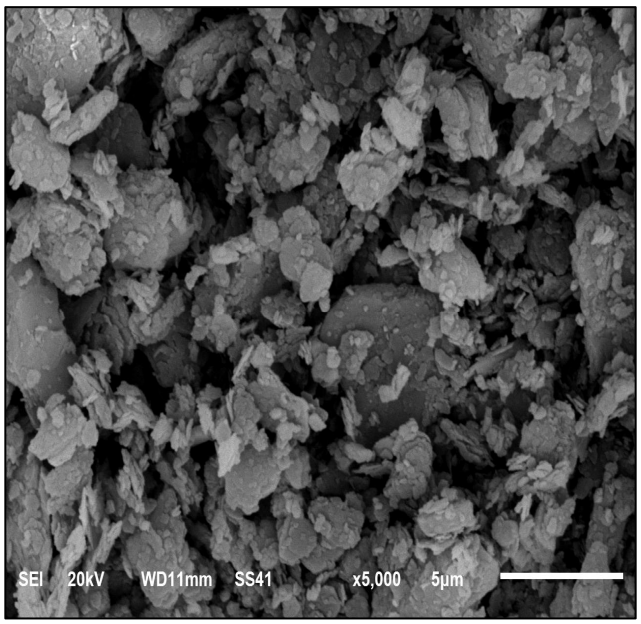



**Figure 6.** SEM Image of MK particles.

The slump values of concrete mixes in group-2 that were produced with MW can be seen in Table 3. The effect of replacing TW with MW in all the mixes of group-2 compared with those in group-1 is shown in Figure 7. With the presence of MW, the concrete slump slightly increased by 1–3% due to the ability of MW to disperse the cementitious material particles (magnetic field effect) [27]. This resulted in the relatively smooth movability of the concrete matrix and hence, a slump increase [36,37]. Previous studies on concrete made with MW have shown that MW has a remarkable effect on concrete slumps. Keshta et al. [36] reported that using MW improved the slump values of volcanic concrete by up to 8%; Ahmed et al. [27] reported no effects on the workability of silica fume concrete when the MW was used; and Elshami et al. [38] reported an increase in the slump flow values by up to 12% when MW was used in self-compacting concrete.

### *3.2. Concrete Mechanical Properties*

#### 3.2.1. Compressive Strength

Table 4 demonstrates the measured mechanical properties of all mixes in this study. At a room temperature of 18 °C, using MK in concrete mixes with TW (group-1) showed a variable effect on its compressive strengths after 7, 28, and 365 days, as shown in Figure 8. At 7 days of concrete age, using 5% MW as cement replacement or additive decreased the compressive strength by about 9%. As the MK content increased beyond 5%, the compressive strength losses were recovered in mix K10T and showed the same strength as the corresponding control mix K0T. The strength kept increasing while the MK content increased and was enhanced by 8% in mix K20T compared with the control mix K0T. When using MK as a cement additive with 10% content, the compressive strength increased by 10%; however, it decreased by 13% when the content was increased to 20% in mix K + 20T. At 28 days of concrete age, using MK as cement replacement or additive led to a 14% increase in compressive strength, except in mix K + 20T, in which the compressive

strength decreased by 14%. At 365 days of concrete age, using MK as cement replacement or additive showed a variable effect on the concrete compressive strength measured at 18 °C, with up to ±12% strength increase, and the highest increase at that concrete age was reported in mix K + 10T. Compared with the corresponding compressive strength after 28 days measured at room temperature (18 °C), the tested mixes led to the development of 71% compressive strength at 365 days, as shown in Figure 8. The rate of this strength development increased with the increase in the MK content.

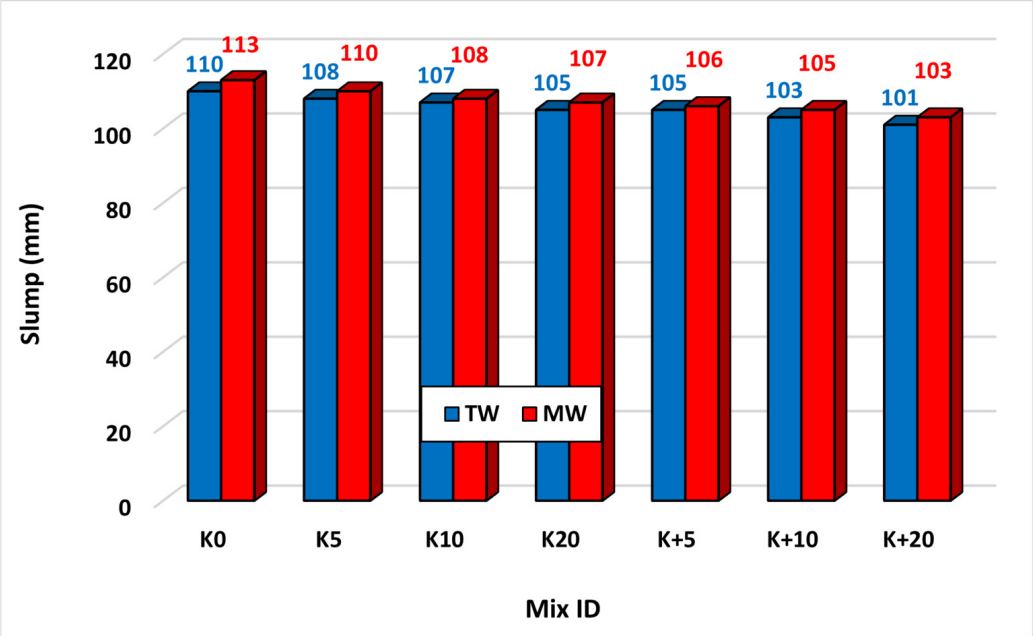



**Figure 7.** Effect of MW on MK concrete slumps.

**Table 4.** Results of the measured mechanical properties.

| Group | Mix ID | Compressive Strength (MPa) | | | | Splitting Tensile Strength (MPa) | Flexural Strength (MPa) |
|---|---|---|---|---|---|---|---|
| | | @ 18 °C | | | @ 100 °C | @ 18 °C | @ 18 °C |
| | | 7 d | 28 d | 365 d | 365 d | 28 d | 28 d |
| 1 | K0T | 39 | 44 | 75 | 56 | 3.82 | 8.70 |
| | K5T | 36 | 44 | 70 | 57 | 3.95 | 9.20 |
| | K10T | 39 | 45 | 73 | 59 | 4.25 | 9.50 |
| | K20T | 42 | 45 | 77 | 60 | 4.23 | 9.10 |
| | K + 5T | 35 | 45 | 68 | 58 | 4.28 | 9.80 |
| | K + 10T | 43 | 50 | 84 | 70 | 4.50 | 10.20 |
| | K + 20T | 34 | 38 | 65 | 56 | 4.15 | 9.65 |
| 2 | K0M | 51 | 57 | 85 | 74 | 5.15 | 11.50 |
| | K5M | 46 | 54 | 74 | 64 | 5.25 | 11.52 |
| | K10M | 51 | 55 | 78 | 70 | 5.55 | 11.60 |
| | K20M | 45 | 50 | 78 | 67 | 5.65 | 11.30 |
| | K + 5M | 48 | 53 | 80 | 71 | 5.30 | 12.50 |
| | K + 10M | 52 | 58 | 95 | 86 | 5.90 | 13.35 |
| | K + 20M | 40 | 50 | 74 | 66 | 5.20 | 11.90 |

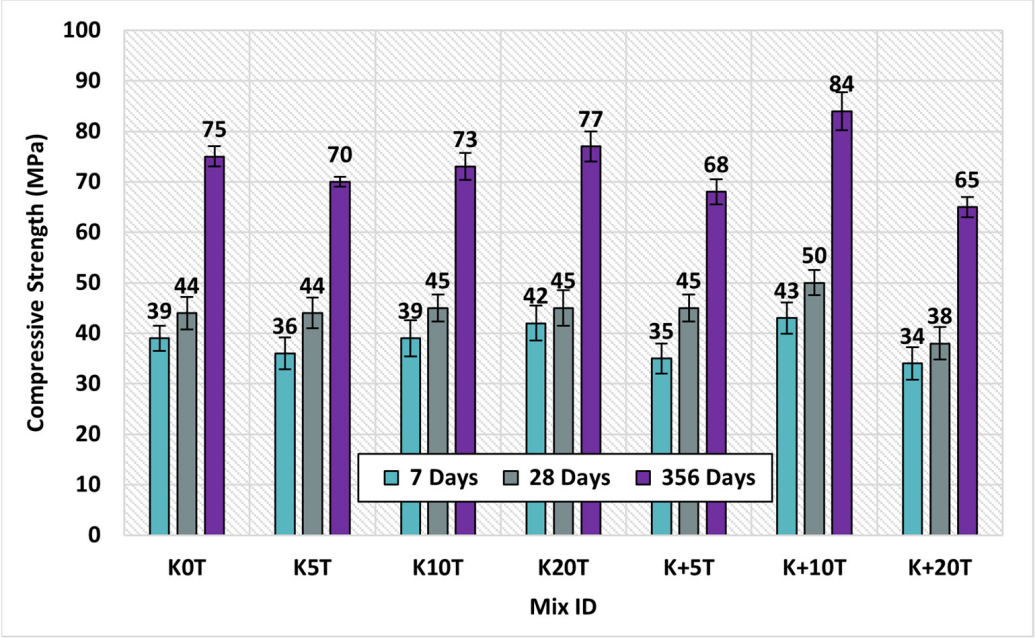



**Figure 8.** Compressive strength of MK concrete made with TW and tested at 18 °C.

From the above compressive strength results, it can be concluded that the positive effect of MK in concrete can be seen at later concrete ages of 28 and 365 days, especially when it is used as an additive to cement with 10% content. The strength enhancement can be attributed to the reaction of MK with the CH produced from the cement hydration process and the generation of the C-S-H gel. As the content of the C-S-H gel increases in concrete, the compressive strength increases [36,48].

Using MW in group-2 mixes significantly enhanced the room temperature concrete compressive strength at 7, 28, and 365 days of concrete age, as shown in Figure 9. At 7 days, when using MW instead of TW with 0%, 5%, 10%, 20%, +5%, +10%, and +20% MK, the compressive strength increased by 31%, 28%, 31%, 7%, 37%, 21%, and 18%, respectively; while at 28 days, the compressive strength increased by 30%, 23%, 22%, 11%, 18%, 16%, and 32%, respectively. At 365 days, the compressive strength increased by 13%, 6%, 7%, 1%, 18%, 13%, and 14%, respectively. The enhancement in the MK concrete compressive strength when using MW is attributed to the relatively small clusters of MW that increase the water activity and the hydration of cementitious materials. The relatively small clusters of MW can penetrate the cementitious material particles easily, which produces more of the C-S-H gel, and hence, better compressive strength [37,49–51]. Using MW with 10% MK as the cement additive (mix K + 10M) showed the highest compressive strength at all ages.

The effect of exposing MK concrete to the relatively high temperature of 100 °C on its compressive strength was measured at 365 days, as shown in Figures 10 and 11. As shown, the MK concrete compressive strength was negatively affected by the exposure to a relatively high temperature, regardless of the use of TW or MW. Compared to the compressive strength at 18 °C, exposing concrete to 100 °C for 8 h decreased the compressive strength by 25%, 19%, 19%, 22%, 15%, 17% and 14%, respectively, when using 0%, 5%, 10%, 20%, +5%, +10%, and +20% MK with TW. This represents a 20% and 15% loss in average strength when MK was used as cement replacement and cement additive, respectively, and represents a 19% total loss in average strength for all mixes made with MK and TW (group-1) compared to the compressive strength at 18 °C.

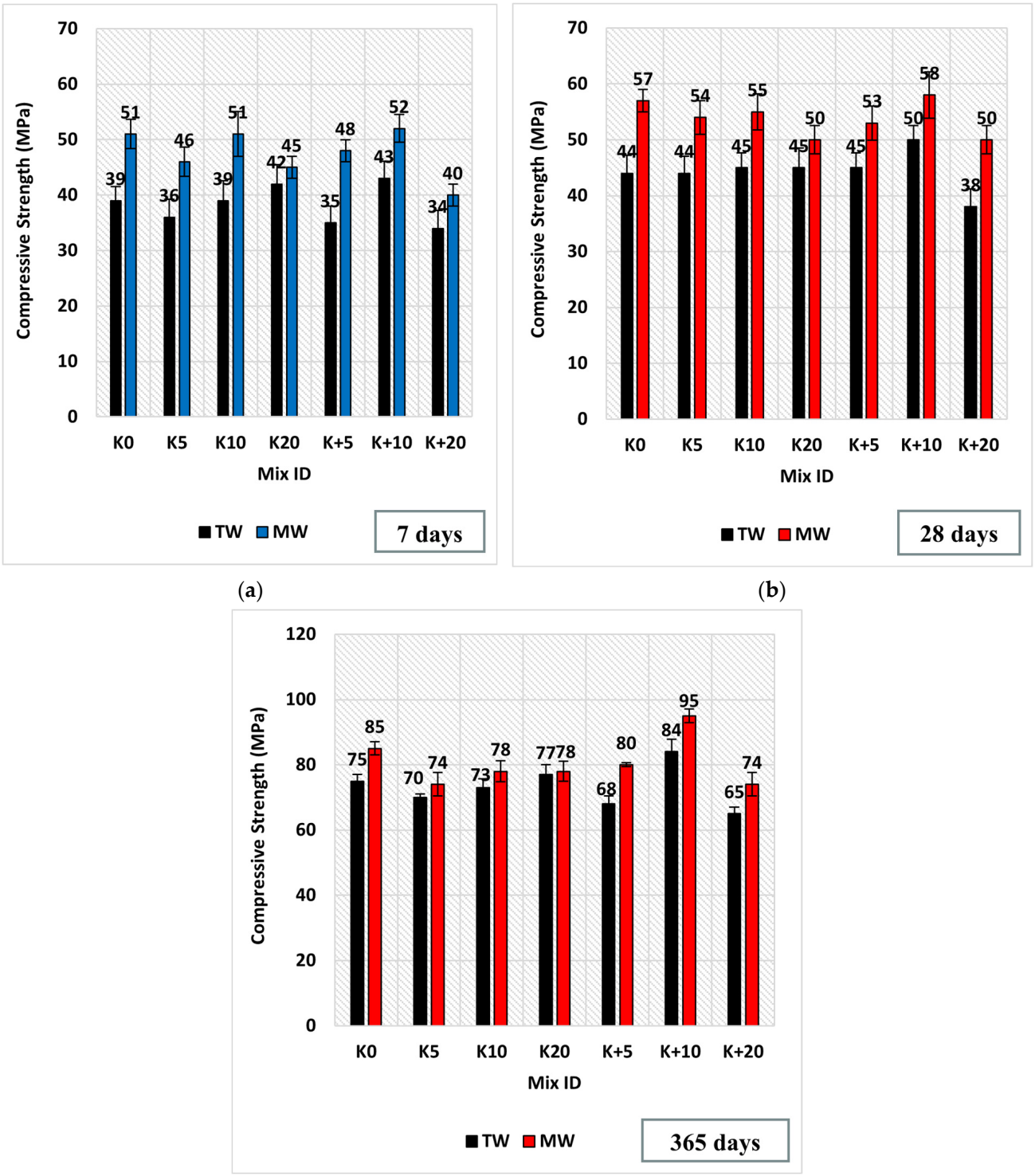



**Figure 9.** Effect of MW on the MK concrete compressive strength at: (**a**) 7 days, (**b**) 28 days, and (**c**) 365 days.

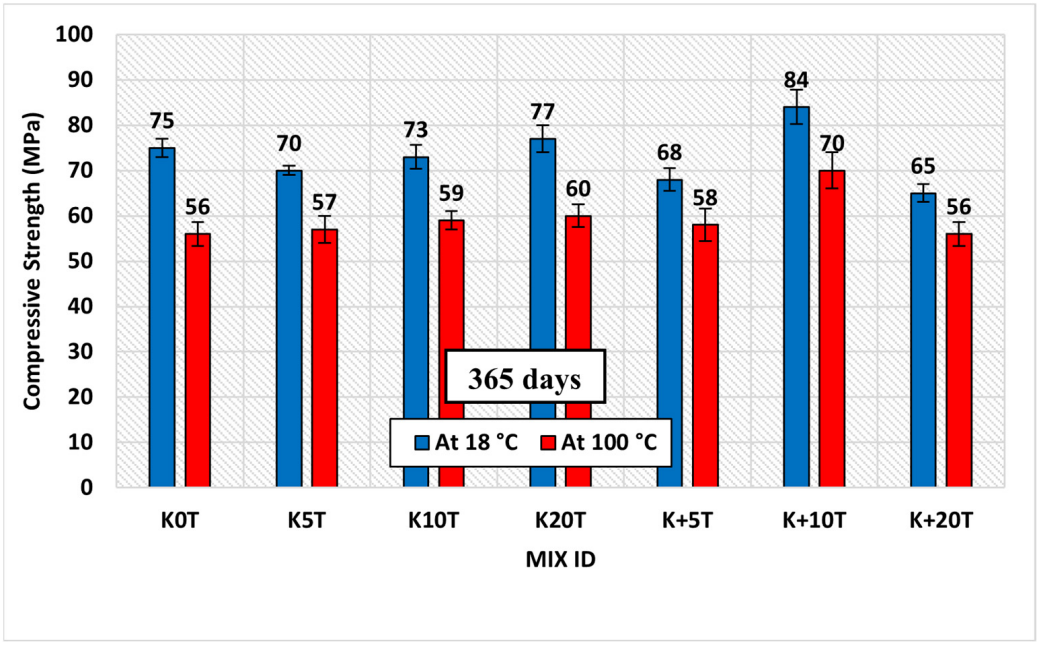



**Figure 10.** Effect of elevated temperature on compressive strength of MK concrete mixed with TW.

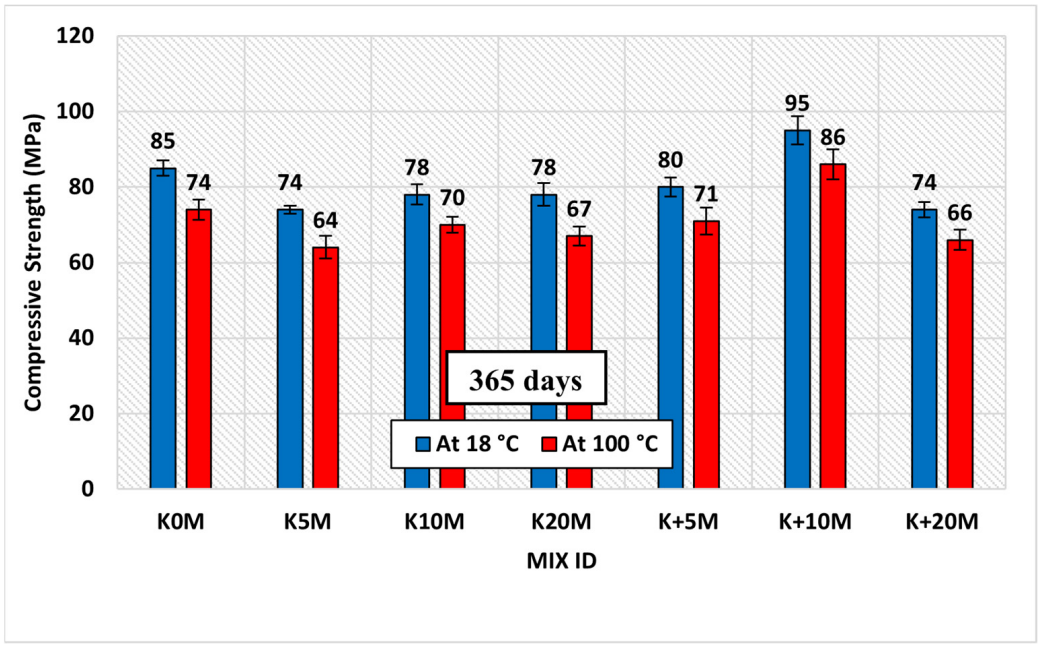



**Figure 11.** Effect of elevated temperature on compressive strength of MK concrete mixed with MW.

On the other hand, using MW instead of TW in MK concrete showed relatively lower strength losses under the relatively high temperature. Compared to the compressive strength at 18 °C, exposing concrete to 100 °C for 8 h decreased the compressive strength by 13%, 14%, 10%, 14%, 11%, 9% and 11%, respectively, when using 0%, 5%, 10%, 20%, +5%, +10%, and +20% MK with MW. This represents a loss of 13% and 11% in the average strength when MK was used as cement replacement and cement additive, respectively, and represents a 12% total loss in average strength for all mixes made with MK and MW (group-2) compared to the compressive strength at 18 °C.

The different coefficients of thermal expansion of the concrete ingredient cause thermal inconsistencies when exposing concrete to a relatively high temperature [51,52]. This results in concrete cracking due to the variable volume changes within the concrete matrix, and hence, concrete strength reduction. The relatively lower losses in MK concrete strength under the relatively high temperature when using MW are attributed to the relatively small clusters of MW that cause well-dispersion of the air voids within the concrete matrix when the concrete gets dry. This results in a less negative effect of the elevated temperature on the concrete strength due to the poor thermal conductivity of the air compared to the other solid ingredients of concrete.

### 3.2.2. Tensile and Flexural Strengths

Figures 12 and 13 show the measured splitting tensile and flexural strengths at 28 days, respectively, for all the mixes in this study. As shown in the figures, the same trend of results for the compressive strength is also obtained for both splitting tensile and flexural strengths. Partially replacing the concrete cement with 5%, 10%, and 20%, MK increased its splitting tensile strength by 3%, 11% and 11%, respectively (Figure 12) and increased the flexural strength by 6%, 9%, and 5%, respectively (Figure 13). Using MK as an additive to cement by 5%, 10%, and 20% increased the splitting tensile strength of the concrete by 12%, 18% and 9%, respectively (Figure 12), and increased the flexural strength by 13%, 17%, and 11%, respectively (Figure 13). The increase in the tensile and flexural strengths when using MK is attributed to its filling effect due to its relatively smaller particle size compared to cement and its ability to react with CH in the concrete creating C-S-H that enhances the bond within the concrete matrix, hence, increasing the tensile and flexural strengths.

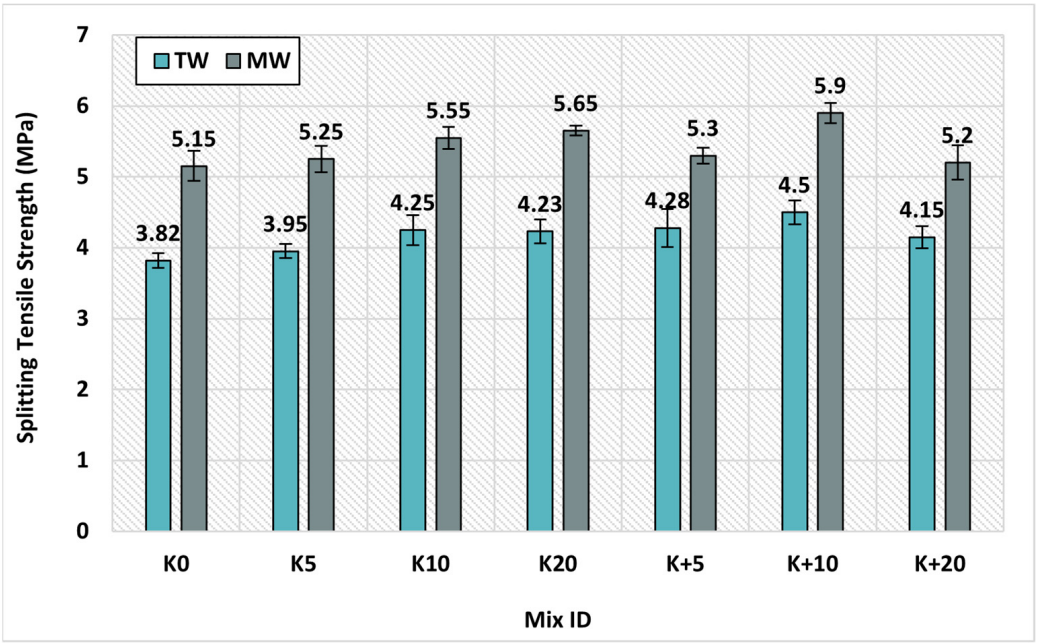



**Figure 12.** Effect of different ratios of MK and MW on the concrete splitting tensile strength after 28 days.

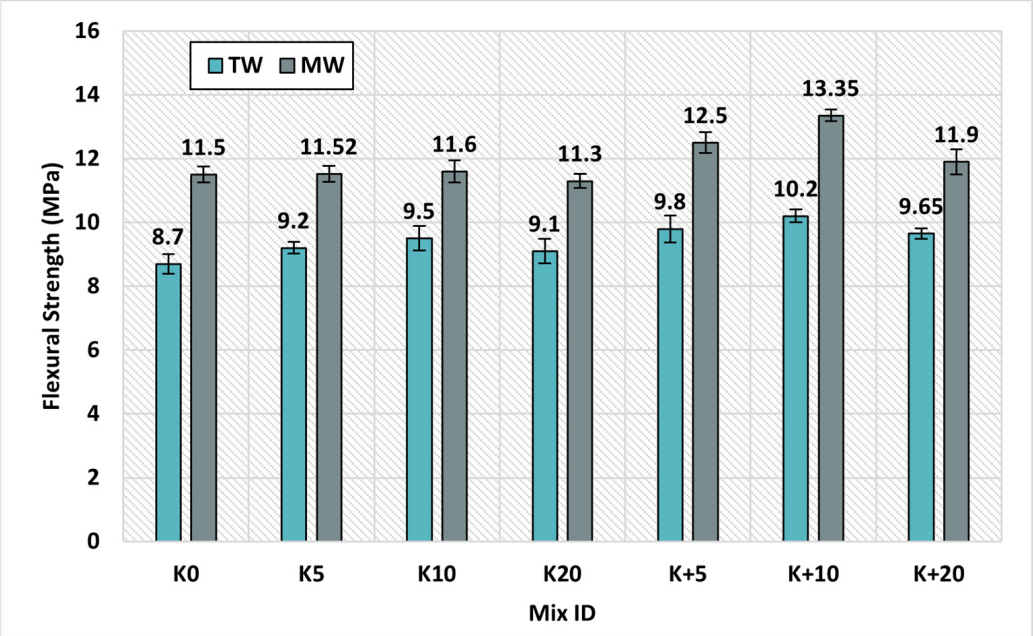



**Figure 13.** Effect of different ratios of MK and MW on the concrete flexural strength after 28 days.

Using MW in group-2 mixes significantly enhanced the concrete splitting tensile strength and flexural strength, as shown in Figures 12 and 13. When using MW instead of TW with 0%, 5%, 10%, 20%, +5%, +10%, and +20% MK, the splitting tensile strength increased by 35%, 33%, 31%, 34%, 24%, 31%, and 25%, respectively, while, the flexural strength increased by 32%, 25%, 22%, 24%, 28%, 31%, and 23%, respectively. The positive effect of MW on both the splitting tensile and flexural strengths is due to the same reasons that enhance the corresponding compressive strength. The best results of splitting tensile strength and flexural strength were shown when 10% MK was used as a cement additive with the presence of MW (mix K + 10M).

### *3.3. Concrete Microstructure and Chemical Analyses*

Figure 14 presents the SEM images of mixes K0T, K0M, K + 10T, and K + 10M. The extent of C-S-H generation is presented in all SEM images with different amounts based on the concrete ingredients. Figure 14a shows relatively fewer crystalline C-S-H gel particles (mix K0T) compared to the more intermixed C-S-H gel that is presented in Figure 14c when using 10% MK as a cement additive with TW in the mix K + 10T. This indicates the ability of MK to improve the concrete microstructural characteristics. The presence of MW enhanced the concrete microstructure by increasing the C-S-H, decreasing the CH, and densifying the concrete matrix, as shown in Figure 14b,d. Furthermore, compared to other mixes, relatively more crystals can be detected in the concrete mixes with MK and MW. This decreased the cracks and pores in the concrete matrix and hence, increased the compressive strength. The combination of MK and MW in the mix K + 10M (Figure 14d) showed a remarkable microstructural shape among other scanned mixes, as it showed relatively dense concrete with a high degree of homogenization between its components. This revealed the enhancements reported in the mechanical properties of mix K + 10M.

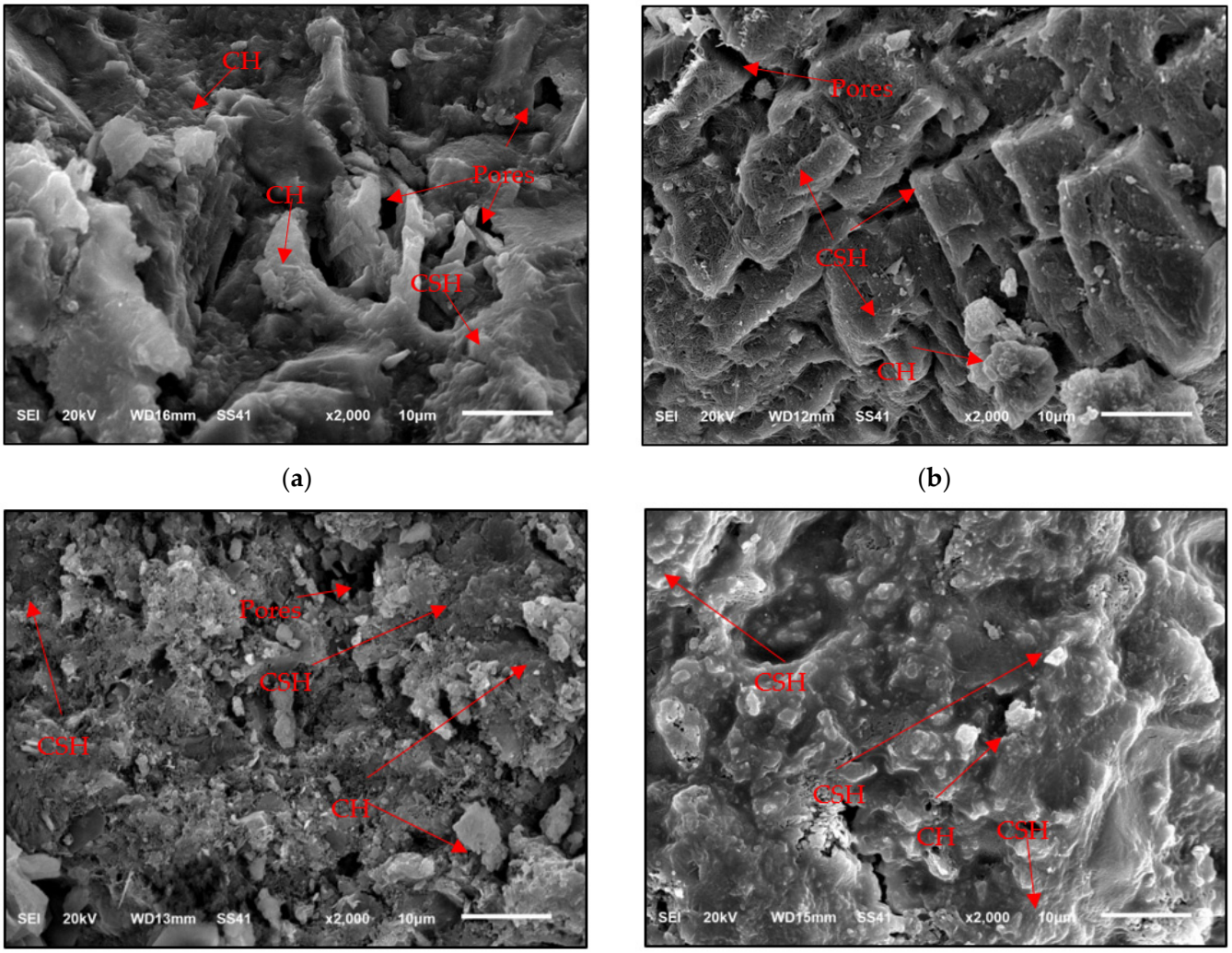



**Figure 14.** SEM images of mixes: (**a**) K0T, (**b**) K0M, (**c**) K + 10T, and (**d**) K + 10M.

Figure 15 and Table 5 show the results of the EDX analysis for concrete mixes K0T, K0M, K + 10T, and K + 10M. The major elemental components of the cementitious mix are calcium (Ca), silica (Si), oxygen (O), aluminum (Al), and sodium (NA), as can be observed in Figure 15. The EDX analysis results showed an increase in the ratio of "O" for mixes K0MW and K + 10M. This confirms the ability of MW to enhance the hydration rate and the formation of the C-S-H gel, both of which resulted in compressive strength enhancement. In addition, the presence of "Si" in mixes K10 + T and K10 + M confirms the reaction between CH and MK that generates the C-S-H gel. By adding this gel to the internal interstitial spaces of the concrete, the concrete can be strengthened, which results in increasing the concrete compressive strength.

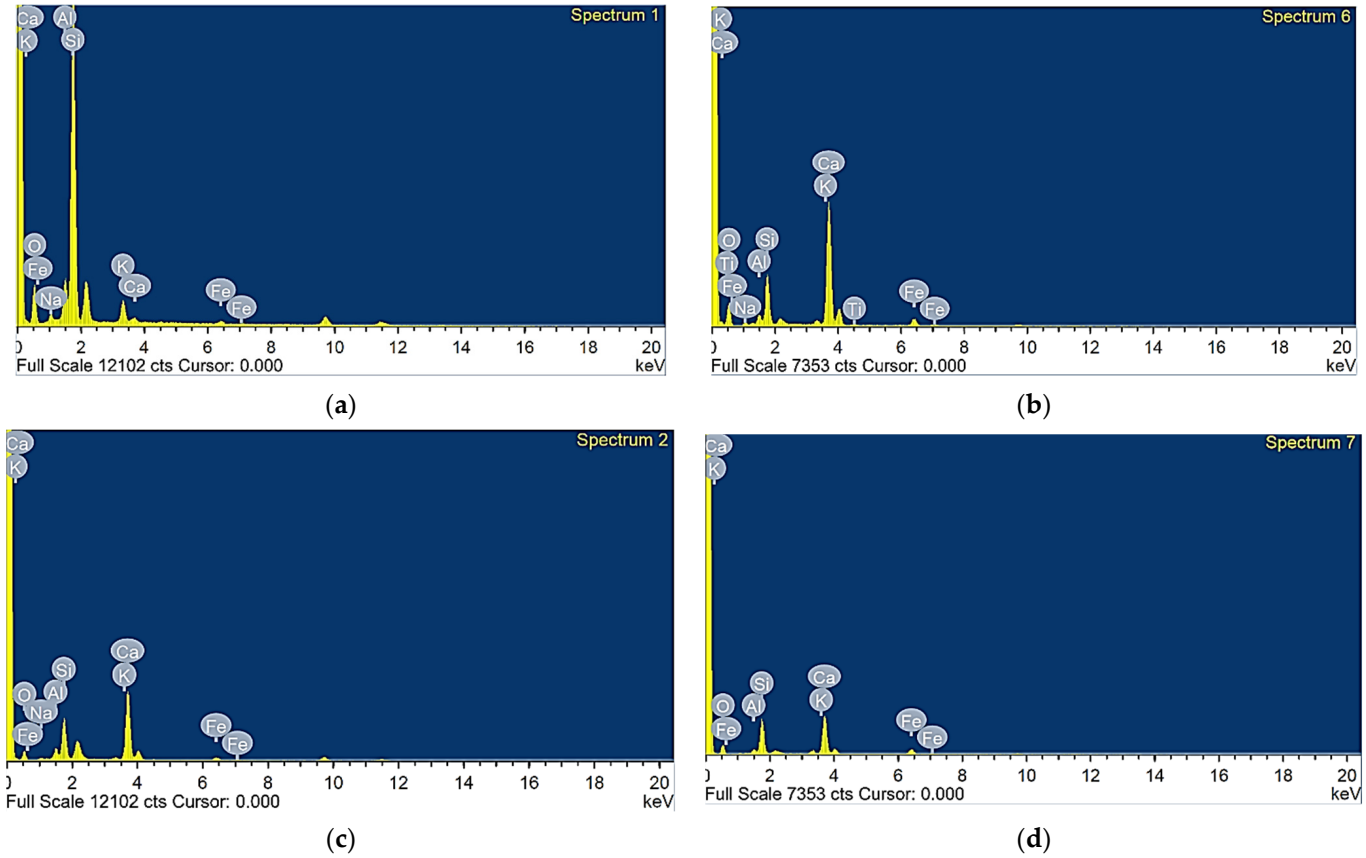
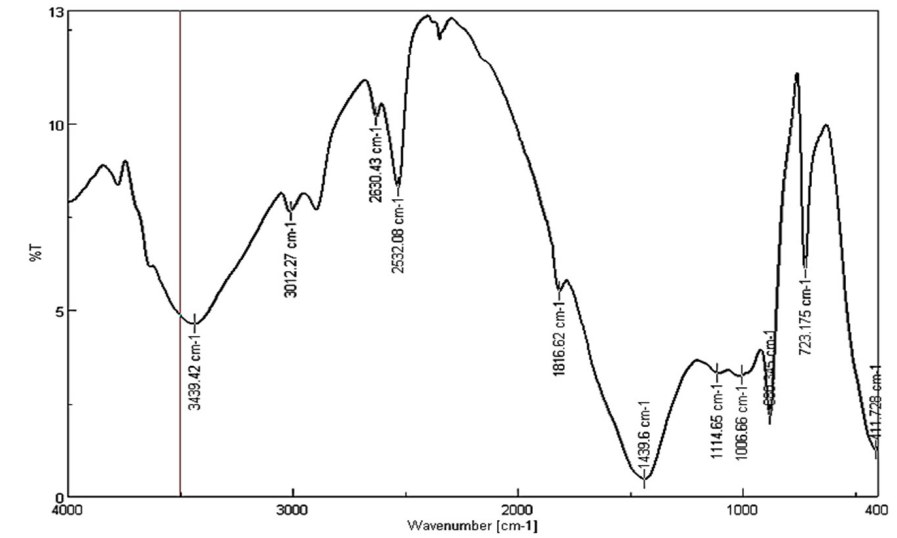



**Figure 15.** EDX analysis of concrete mixes: (**a**) K0T, (**b**) K0M, (**c**) K + 10T, and (**d**) K + 10M.

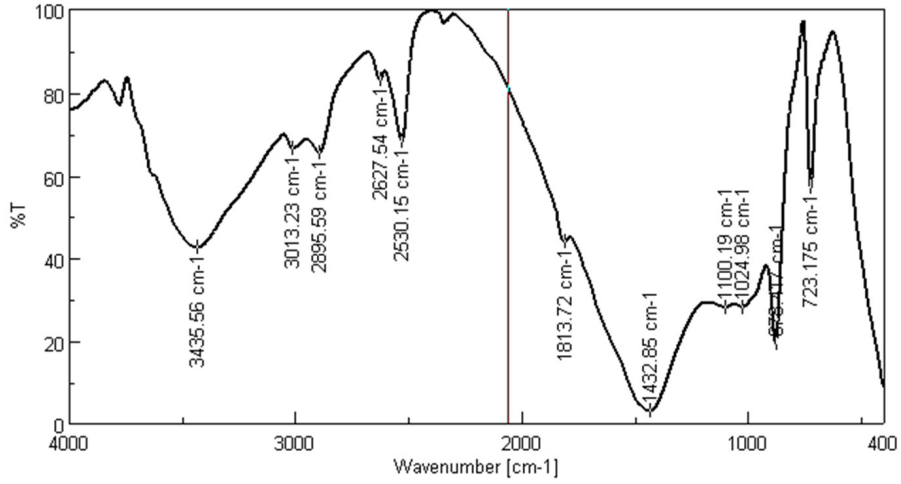
**Table 5.** Concrete EDX analysis results.

| Mix | K0T | | K0M | | K + 10T | | K + 10M | |
|---|---|---|---|---|---|---|---|---|
| **Element** | **Weight%** | **Atomic%** | **Weight%** | **Atomic%** | **Weight%** | **Atomic%** | **Weight%** | **Atomic%** |
| O K | 43.14 | 57.47 | 59.96 | 76.59 | 46.17 | 64.25 | 52.67 | 70.55 |
| NA K | 1.93 | 1.79 | 1.47 | 1.31 | 1.68 | 1.63 | -- | -- |
| Al K | 5.06 | 4.00 | 2.29 | 1.74 | 4.51 | 3.72 | 2.40 | 1.91 |
| Si K | 45.30 | 34.38 | 10.29 | 7.49 | 17.94 | 14.22 | 18.62 | 14.21 |
| K K | 3.33 | 1.81 | 0.78 | 0.41 | 0.80 | 0.46 | 1.79 | 0.98 |
| Ca K | 0.53 | 0.28 | 22.39 | 11.42 | 26.76 | 14.87 | 19.51 | 10.43 |
| Fe K | 0.72 | 0.28 | 2.55 | 0..93 | 2.13 | 0.85 | 5.01 | 1.92 |
| Ti K | -- | -- | 0.27 | 0.12 | -- | -- | -- | -- |

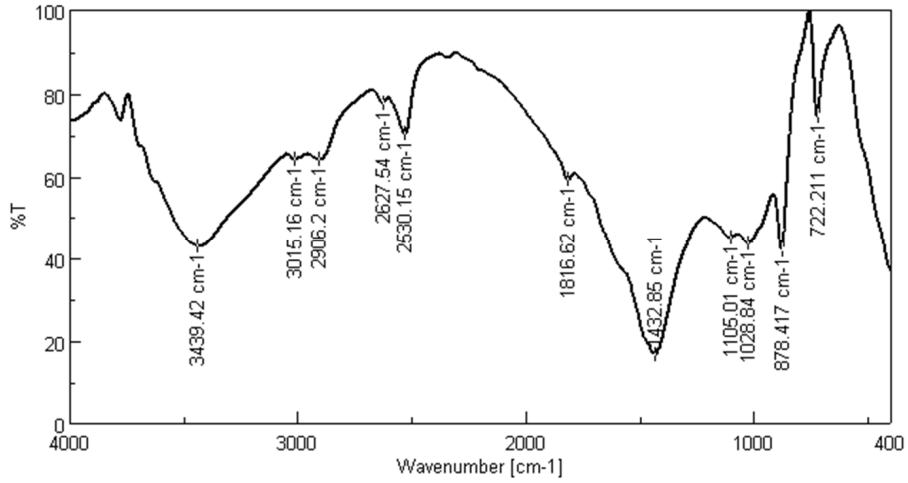
Figure 16 shows the FTIR analysis of concrete mixes K0T, K0M, K + 10T, and K + 10M. As presented in the figure, the vibrational bands at 722–723 $cm^{-1}$ are related to the ring vibrations of the Si-O bond. The bands observed at 1800–3430 $cm^{-1}$ are characteristic of the stretching and bending vibrations of the O-H groups. The existence of O-H groups in all mixes indicates the hydrogen bonds with water and also indicates the existence of the silanol group Si-O-H which is formed by the hydration of $SiO_2$. In the mixes made with MW (K0M and K + 10M), these bands were relatively less than those in the mixes made with TW (K0T and K + 10T). The Si-O-H band in the mixes made with 10% MK (K + 10T and K + 10M) is relatively more than that in the mixes made with 0% MK (K0T and K0M).




(**a**)

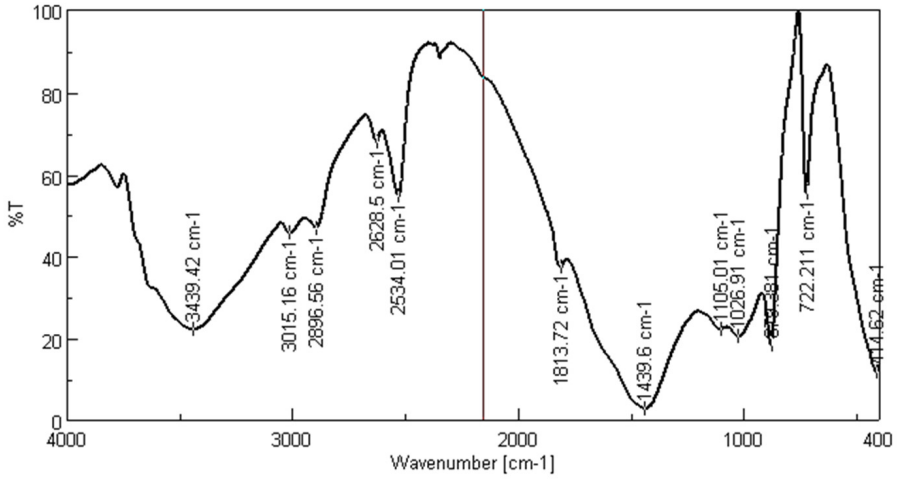



(**b**)




(**c**)

**Figure 16.** *Cont*.




(**d**)

**Figure 16.** FTIR analysis of concrete mixes: (**a**) K0T, (**b**) K0M, (**c**) K + 10T, and (**d**) K + 10M.

## 4. Conclusions

This experimental study investigated the effect of using metakaolin (MK) as supplementary cement material and magnetized water (MW) as concrete mixing water on concrete performance. Concrete mechanical characteristics, microstructures, and chemical compositions were experimentally evaluated. The MK was used as a cement replacement or additive by six ratios: 5%, 10%, 20%, +5%, +10%, and +20%. The MW was produced using two magnetic fields with intensities of 1.6 tesla and 1.4 tesla. The key findings of this research can be summarized in the following points:

- Increasing the MK content in concrete decreased its slump by up to 8% when TW was used. However, using MW instead of TW enhanced the MK concrete slump by up to 3%.
- Using 10% of MK as a cement additive (+10%) showed the best results as it enhanced the compressive strength, splitting tensile strength, and flexural strength by 14%, 18%, and 17%, respectively, at 28 days when using TW. Using MW instead of TW in MK concrete increased the compressive, splitting tensile, and flexural strengths after 28 days by up to 32%, 35%, and 32%, respectively.
- A negative effect on MK concrete compressive strength was reported when exposing it to a relatively high temperature, in which a 19% total average strength loss occurred in mixes made with MK and TW; however, with the presence of MW, the total average strength loss decreased to 12%.
- The results of the SEM analysis showed indications of more C-S-H gel production and less CH and pores when using MW in MK concrete. This was also confirmed by the conducted chemical analyses.

Overall, using magnetized water in metakaolin concrete enhanced its mechanical and microstructural characteristics. It is recommended for future studies to employ magnetized water in different types of concrete, such as self-compacting concrete, volcanic concrete, rubberized concrete, and lightweight concrete. It is also recommended to experimentally investigate the effect of metakaolin on several durability properties of concrete.

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