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Utilizing of Magnetized Water in Enhancing of Volcanic Concrete Characteristics

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Abstract: Volcanic concrete is an eco-friendly concrete type in that it contains coarse and fine aggregates that all extracted from the igneous volcanic rock. However, utilizing of volcanic ash (VA) as partial/full replacement of concrete cement significantly affects the concrete workability, especially at high cement replacement ratios. This has also some adverse effects on concrete strength. Utilizing magnetized water (MW) in concrete as a partial/full replacement of ordinary tap water (TW) has a notable effect on enhancing the fresh and hardened concrete properties. This research aims to study the effect of using MW prepared in a magnetic field of 1.4 Tesla on the workability and hardened properties (compressive, tensile, and flexural strengths) of volcanic concrete. In this study, VA partially replaced volcanic concrete cement with ratios of 5%, 10%, 15%, and 20%. Ten volcanic concrete mixes were prepared in two groups. The first one was prepared with VA (0–20%) and mixed with TW. The other group was prepared with the same VA contents like group one, but mixed with MW. Microstructure imaging for volcanic concrete was also conducted in this study. Results of water tests showed 17% and 15% increase in total dissolved solids (TDS) and pH, respectively, of MW compared with those of TW. In addition, the water magnetization decreased the water surface tension by 7% compared with that of TW. Results of hardened concrete tests showed that the best ratio of VA in volcanic concrete was 5% with and without using magnetized water. The volcanic concrete slump decreased when using TW; however, using MW enhanced the volcanic concrete slump by up to 8%. The compressive strength was improved by 35%, 23%, and 20% at 7 days, 28 days, and 120 days, respectively, with no VA and with the presence of MW. The compressive strength was improved by 11%, 12%, and 11% after 7 days, 28 days, and 120 days, respectively, with using 5% VA and with the presence of MW. Both splitting tensile strength and flexural strength of volcanic concrete with and without VA or MW behaved similar to that of the corresponding compressive strength.

Keywords: magnetized water; magnetic field; volcanic concrete; volcanic ash; concrete characteristics

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1. Introduction

Concrete is the most prevalent construction material around the world due to its applicability in a wide range of construction applications [1–3]. Cement is a concrete component that is a non-environmentally friendly material. The production of cement is responsible for more than 6% of all worldwide carbon dioxide (CO_2) emissions which causing global warming. Cement manufacturing accounts for 95% of all CO_2 emissions when producing a cubic meter of concrete [4]. Volcanic concrete is an eco-friendly concrete type that contains materials extracted from the igneous natural volcanic rock. Volcanic rock crushed in different sizes can work as coarse, fine, and cementitious material in concrete. Volcanic ash (VA) is an inert siliceous pozzolanic material that when combined with lime in the presence of water, it forms a cementitious matter with high structural qualities [5]. It can effectively fill the voids between the larger particles, reduce the heat of hydration, and react with calcium hydroxide ($Ca(OH)_2$) to generate calcium silicate hydrate (CSH) [6–8]. The main component of volcanic concrete is volcanic ash due to the importance of utilizing it as a pozzolanic material and as a replacement of cement which provides a high-performance strength at a low cost.

Around 124 million hectares, or 0.84% of the world's land surface, contain deposits of VA materials, 60% of which are found in tropical areas [9]. When compared to the conventional quarrying approach frequently employed for clay mining, these deposits are more readily accessible, can be naturally mined, and have a better cost-benefit ratio. Additionally, because the VA can be used in the creation of blended cement, these deposits can have great commercial significance for the cement industry in densely populated countries with rapid economic expansion [10]. For the mineral and chemical composition of VA, Alumina (Al_2O_3) and silica (SiO_2) are the two most crucial and important VA components. Other pozzolanic oxides, such as ferric oxide (Fe_2O_3) and magnesium oxide (MgO), which are frequently found in acidic rock, can also be present in low amounts in VA [5]. Due to the presence of carbonates and clay minerals, some vitreous forms of VAs exhibit a significant loss of ignition (LOI), which denotes the presence of water and CO_2 [11]. The magma's composition and the eruption conditions affect the mineral content of VA. Minerals with silicate ions are the most frequently discovered in VA. There are several types of silicate minerals, including feldspars such as albite and anorthite, amphiboles such as tremolite, and pyroxenes such as augite, diopside, and less common quartzes [12,13]. For the physical properties, according to the ASTM C204 criteria, the specific surface area (SSA) of VA ranges from 240 to 1640 m^2/kg, which is typically finer than that of the ordinary Portland cement (OPC) (SSA of OPC is 367 m^2/kg) [14]. Before combining the VA with cement, the sandy fraction can be removed, and the VA can also be ground to a finer particle size [5].

For the pozzolanic effect of volcanic ash to use as supplementary material, some researchers study the strength activity index (SAI) of VA. The SAI value of paste combinations containing six types of VAs from basalt, olivine andesite, amphibole-biotite andesite, rhyodacite, and scoria was calculated by Labbaci et al. [15]. The SAIs of all the combinations were roughly between 82.11% and 91.91% that of the traditional mortar SAIs at 28 days. These results reveal that an increase in the active vitreous phases, which have a higher SiO2 and Al_2O_3 content, is closely correlated with the pozzolanic activities of VAs, as measured by the SAI. Hossain [16] used 0–40% of VA material in place of OPC to conduct a SAI test. The established SAI at 7 days and 28 days were 78–100% and 67–100% of compressive strength, respectively, obtained using a 100% conventional mixture of OPC. Cement pastes were created by Kupwade-Patil et al. [17] who utilized 50% OPC and 50% of two different types of milled VA components. The average size of the particles in one type of VA material was 6 μm, whereas the particles in the other type of VA material were 17 μm. The compressive strength of the samples created with the 6μm VA particles was 15% greater than the samples created with the 17μm VA particle. Due to the high energy required for milling, samples made with the 6 μm VA particles had embodied energy values that were 4% higher than samples made with the 17 μm VA particles.

Magnetized water (MW) is ordinary tap water treated in a magnetic field in which it passed through a certain magnetic field intensity generated by an electromagnet or permanent magnet [18,19]. This revolutionary water treatment technique is pollution-free, low-cost, non-chemical, and environmentally friendly, with a low installation charge [20]. Some researchers argue that the magnetization process has little effect on the qualities of water, while others claim that it can improve the physicochemical and bacteriological quality of regular tap water in a variety of applications including: achieving greater concrete compressive strength [21], reducing precipitation rate of calcium carbonate [22], and improving concrete plant productivity. Water that has been magnetized does not have a force or the ability to attract other materials; rather, it has been exposed to a magnetic field strength that has been discovered to alter the structural composition and physicochemical qualities of conventional water [23]. Magnetic force can break down these water clusters into a small cluster or single water molecules when tap water passes through magnetic flux as shown in Figure 1. As a result, water activity increases, solubility increases, and availability of water for hydration increases. Magnetized water can easily access the core region of cement particles during the hydration reaction, making it more effective that resulting in greater quality and density for cement hydration products [24]. Su N, and Wu. [25] achieved 15–20% increase in mortar compressive strength when using MW treated in magnetic field of 0.8 T or 1.2 T. Su et al. [26] investigated the compressive strength and workability of both concrete and mortar made with using MW and granulated blast furnace slag. The compressive strength of mortar samples increased by 9–19% and the concrete sample increased by 10–23%. Weilin et al. [27] found that magnetic treatment of slurry resulted in a considerable increase in cement compressive strength by 54%, cement bending strength by 39%, and cement bonding strength by 20%. They also showed that after the magnetization process, the initial setting time and final setting time of slurry decreased by 39% and 31%, respectively. Saddam [28] examined the effect of current velocity and water flow rate on concrete compressive strength and consistency in order to determine the best water treatment characteristics. The results showed that when the velocity and discharge of water were equal to 0.71 m/s and 0.22 L/s, respectively, the best increase in compressive and workability of concrete is achieved.

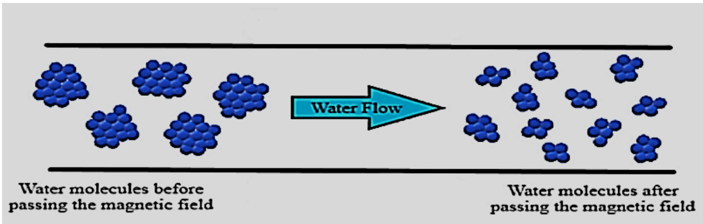


Figure 1. Water molecules after magnetization [29].

From the above literature review, a combination of magnetized water and volcanic ash in volcanic concrete can be promising way to enhance its characteristics. This paper focuses on investigating the effect of magnetized water treated in a magnetic field of 1.4 T on the properties of volcanic concrete with different ratios of volcanic ash (0% to 20%) as a partial replacement of volcanic concrete cement. The research aims to produce sustainable green concrete, reduce cement production and its CO_2 harmful impacts.

2. Experimental Program

2.1. Materials

2.1.1. Cement

The cement used in this study was ordinary Portland cement with specific gravity of 3.15 that undergoes Egyptian standards ES 2421:2009 [30]. The chemical composition of the cement is shown in Table 1.

Table 1. Chemical composition of the cement used.

Oxides	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI	IR	Total
(%)	62.7	20.20	6.00	3.30	2.00	2.20	1.70	1.40	99.50

2.1.2. Aggregate

Fine and coarse particles of natural volcanic rock were used as fine and coarse aggregates, respectively, in this study, see Figure 2. The natural rocks were collected from Wadi El-Anbgy, El-Quseir-Egypt. The fine aggregate had sizes of 5 mm, specific gravity of 2.68, and unit weight of 1650 kg/m^3. The coarse aggregate had sizes of 8–12 mm, specific gravity of 2.68, and unit weight of 1650 kg/m^3.

Figure 2. Volcanic rocks as coarse aggregate, fine aggregate, and volcanic ash.

2.1.3. Volcanic Ash (VA)

Volcanic ash according to Egyptian Standards 4756-1/2013 [31] was used in this study as a pozzolanic material to partially replace volcanic concrete cement. The VA was collected as the passing fines through sieve No. 170 of crushed natural volcanic rocks, see Figure 2. The volcanic rocks were collected from Wadi El-Anbgy, El-Quseir-EYGPT. The VA had a specific gravity of 2.68 and a unit weight of 1650 kg/m^3. The chemical composition of VA is shown in Table 2.

Table 2. The chemical composition of volcanic ash.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total
(%)	67.04	14.90	2.59	3.27	1.72	0.25	3.26	3.28	0.26	0.16	2.83	99.56

The prepared VA was analyzed to check its pozzolanic reactivity by conducting energy-dispersive x-ray (EDX) analysis and thermogravimetric analysis (TGA). Table 3 and Figure 3 shows the EDX analysis results of VA. As shown, VA is mostly comprised of oxygen (O) with 51.66%, silicon (Si) with 30.31%, and alumina (Al) with 6.90%. These are the main elements originally needed in any pozzolanic material to be active in the hydration reaction when it replaces cement. Figure 4 depicts the thermal stability of VA that prepared from the used rocks. The figure shows the effect of thermal effects on VA from 0 °C up to 800 °C with 15 deg/min as a temperature rate using a platinum cell. The TGA peaks cannot be detected up to 800 °C. The TGA changing range is within 0.1 mg, which indicates that the thermal impact of VA is insignificant, and it is stable until temperatures approach 800 °C. Herein, because of the properties of the natural of used rocks, VA has no water content and not to melt with heating. In other words, VA is a stable material when exposed to heat because its source is a volcano eruption. As a result, VA is active without heating and can be used as a pozzolanic material without calcination. These analyses confirm the reactivity of volcanic ash.

2.1.4. Chemical Admixture

Type F (sikament-163) according to ASTM C 494-92 [32] with specific gravity of 1.2 was utilized as a chemical admixture in this study.

Table 3. EDX analysis results of volcanic ash.

Element	(VA) Chemical Weights	
	Weight %	Atomic %
O K	51.66	67.73
NA K	−0.83	−0.75
Al K	6.90	5.36
Si K	30.31	22.64
K K	2.69	1.44
Ca K	1.81	0.95
Fe K	3.98	1.50
Cu K	1.64	0.54
Zn K	1.83	0.59

Figure 3. EDX analysis of VA.

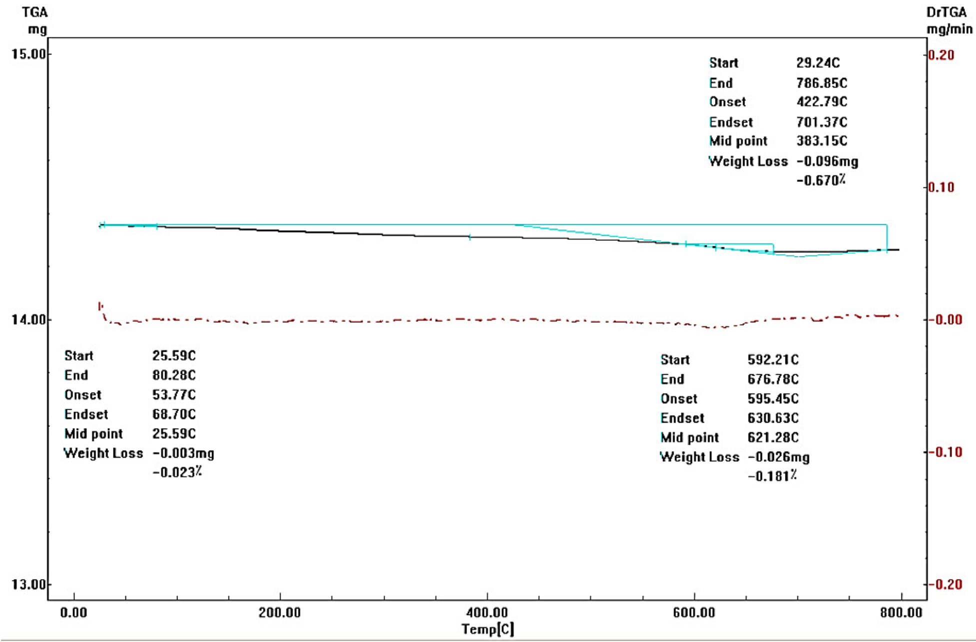


Figure 4. TGA analysis of VA.

2.1.5. Water

The water utilized in this study had two types, namely: regular tap water (TW), and magnetized water (MW). The MW was prepared by circulating regular tap water 150 cycles through a permanent magnet with a magnetic field intensity of 1.4 Tesla, as shown in Figure 5. The optimum number of cycles was chosen according to previous studies [18,23]. This magnet was provided by Delta Water Company, Egypt, whereby the company uses this magnet with an intensity of 1.4 Tesla, which is the best for producing magnetic energy that is able to treat the waste water. That magnetic energy disperses the waste water clusters and produces smaller clusters which can help in separating the salts and unwanted ingredients in the waste water to produce treated water. Previous researchers [18,23,24] have successfully used this 1.4 Tesla magnet to magnetize the tap water for use in concrete mixes production. Table 4 shows the dimensions, description, and other specifications of the magnetic device used. Some physical and chemical properties were measured for both TW and MW for comparison in this study.

Figure 5. Permanent magnet utilized in magnetizing the water.

Table 4. Permanent magnet dimension and description.

Weight	Material	Connection	Total Length	Outer Diameter	Inner Diameter
6 kg	Stainless steel	Thread connection	30 Inches	3 Inches	1 Inch

2.2. Mixes and Variables

The experimental program was divided into two groups with a total number of 10 mixes. In the first group, 5 mixes were prepared with regular TW and in the second group, 5 mixes were pre-pared with MW using the methodology mentioned above. VA with ratios of 0%, 5%, 10%, 15%, and 20% was used as partial replacement of cement in both groups. All mixes had constant dosages of 2% superplasticizer, 500 kg/m^3 cement content, and water to cement ratio of 0.35. The workability, compressive strength, splitting tensile strength, and flexural strength of the two groups were measured. Table 5 shows the mixes design used in this study.

Table 5. Details of mixes used in this study.

Group	Mix ID	Coarse Aggregate	Fine Aggregate	Cement		VA Ratio		TW	MW	SP
		Content (kg/m^3)	Content (kg/m^3)	Ratio	Content (kg/m^3)	Ratio	Content (kg/m^3)	Content (kg/m^3)	Content (kg/m^3)	Content (kg/m^3)
1	V0T	1175	588	100%	500	0%	0	175	–	10
	V5T	1173	586	95%	475	5%	25	175	–	10
	V10T	1170	585	90%	450	10%	50	175	–	10
	V15T	1168	584	85%	425	15%	75	175	–	10
	V20T	1166	583	80%	400	20%	100	175	–	10
2	V0M	1175	588	100%	500	0%	0	–	175	10
	V5M	1173	586	95%	475	5%	25	–	175	10
	V10M	1170	585	90%	450	10%	50	–	175	10
	V15M	1168	584	85%	425	15%	75	–	175	10
	V20M	1166	583	80%	400	20%	100	–	175	10
SP	Superplasticizer		TW	Tap water			MW	Magnetized water		

A pan mixer with a capacity of 60 L was used to mix all concrete mixes. Following the weighing up of all required quantities, the mixing process consisted of mixing cement, VA if used, coarse and fine aggregates for two minutes, then adding half of the water and mix for another two minutes. After that, the remaining water and superplasticizer were added, and mixing was continued for another three minutes. In the mixes containing MW, the water was immediately used in the mix after the magnetization, following the same method used in mixes with ordinary TW. Once the mixing completed, the slump test was conducted according to ASTM C143 [33]. From each mix, nine cubic specimens (100 × 100 × 100 mm) were cast for testing the compressive strength after 7, 28, and 120 days. In addition, two 100 × 200 mm cylinder specimens were cast for testing the splitting tensile strength at 28 days, and two 100 × 100 × 50 mm beams were cast for testing the flexural strength at 28 days. The cast specimens were demolded after 24 h and cured in a water path until testing day.

3. Results and Discussion

3.1. Water Tests

Table 6 shows the results of some physical and chemical properties of TW and MW utilized in this research. The measured properties were: the total dissolved solids (TDS), pH, density, and surface tension to show the different in these properties before and after magnetization. The surface tension was measured by using capillary tubes, where the height of TW or MW is measured inside these tubes. Surface tension can be calculated by the following equation (Equation (1)), where T is the water surface tension, d is the water density, g is the gravitational acceleration, r is the tube radius, and h is the height of water inside the capillary tubes.

$$T = \frac{2}{dgr\left(h + \frac{1}{3r}\right)} \tag{1}$$

Table 6. Results of physical and chemical properties of water.

Property	Unit	Type of Water		Relative Change (%)
		Tap Water (TW)	Magnetized Water (MW)	
Total dissolved solids (TDS)	part per million (P.P.M)	270	315	17
pH	–	7.2	8.3	15
Density	Gm/cm^3	0.972	0.970	0
Surface tension	mN/m	72.34	67.38	−7

As shown in Table 6, for the TDS, MW represented an increase in TDS value by 17% compared with that of TW. This is due to the fact that the magnetic field causes the charges to separate until the restoring force is equal to and in opposition to the field’s force on the charges. As a result, the water molecules in these conditions are different from those in normal conditions, smaller water molecules will form, and there will be more water molecules per unit volume, which will increase the water solubility and TDS [34]. For the pH, water magnetization increased the pH value compared with that of TW by 15% as represented in Table 6. This was attributed to the polarization of water molecules and because the water molecules will arrange in one direction with decreasing hydrogen ion concentration [35]. For the density, there was insignificant effect on water density occurred when the water was magnetized. For the surface tension, as shown in Table 6 the surface tension of the water that exposed to magnetic field decreased by 7% compared with that of regular TW, this might be due to the attraction between water molecules caused by the applied magnetic field because of the increased polarization effect and the changes in the distribution of molecules in MW which caused the drop in surface tension value [36].

3.2. Slump Test

As shown in Table 7, the values of the slump of volcanic concrete of group-1 decreased from 160 mm at 0% VA to 150 mm at 5% VA. Beyond that, the slump decreased to 130 mm at 10% VA, and kept at the same value at 15% and 20% VA. The slump losses with using VA might be due to the relatively small size and high fineness of VA which make it absorbable to the mixing water. In addition, the VA has rough edge polygonal particles (compared with relatively round edge particles for cement [13]), which may decrease the wetting effect and then increase the inter-aggregate frictional resistance. Figure 6 shows scanning electron microscope (SEM) image of VA particles that presents the VA rough edges. Moreover, the attraction force between the VA and cement is high [37] and with cement agglomeration increase, hence less workability. Figure 7 shows the relative values of volcanic concrete slump with using ordinary TW. As shown, at 5%, 10%, 15%, and 20% VA, the slump decreased by 6%, 19%, 12%, and 19%, respectively.

Table 7. Slump values of volcanic concrete.

MIX ID (Group-1)	Slump Value (mm)	MIX ID (Group-2)	Slump Value (mm)
V0T	160	V0M	175
V5T	150	V5M	155
V10T	130	V10M	140
V15T	140	V15M	145
V20T	130	V20M	130

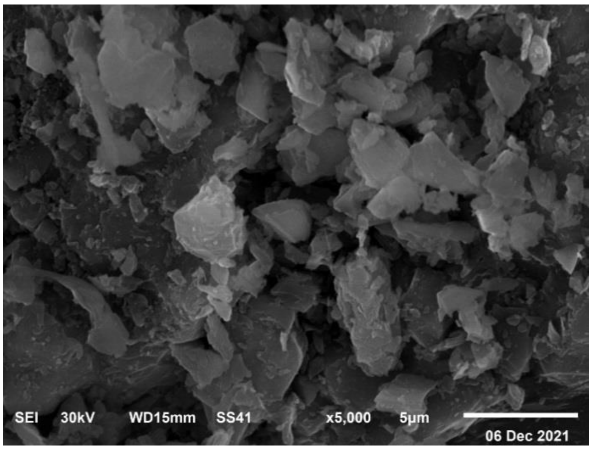


Figure 6. SEM image of VA particles.

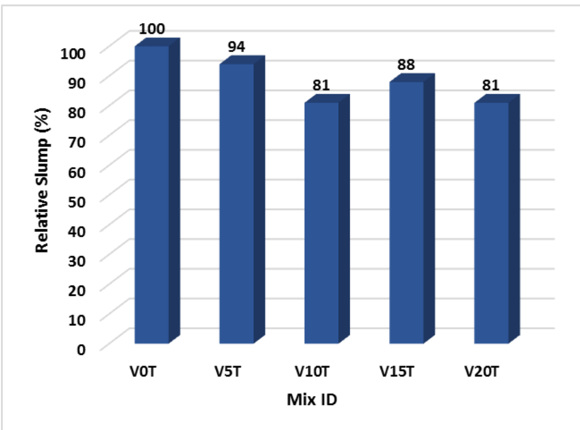


Figure 7. Effect of VA ratio on the slump of volcanic concrete made with tap water.

Table 7 also shows the volcanic concrete slump values of group-2 made with MW. Figure 8 highlights the effect of using MW instead of TW. As shown in the figure, the MW could increase the volcanic concrete slump by 3–8% when used with up to 15% VA content. At 20% VA content, there was no effect of using MW in volcanic concrete. The best slump improvement reported was in mix with 10% VA as it showed 8% slump increase. The slump enhancement using MW is attributed to the dispersing effect of magnetic field on water molecules, which results in dispersing the cementitious material particles and hence, smooth movability of concrete matrix with an increase in its slump.

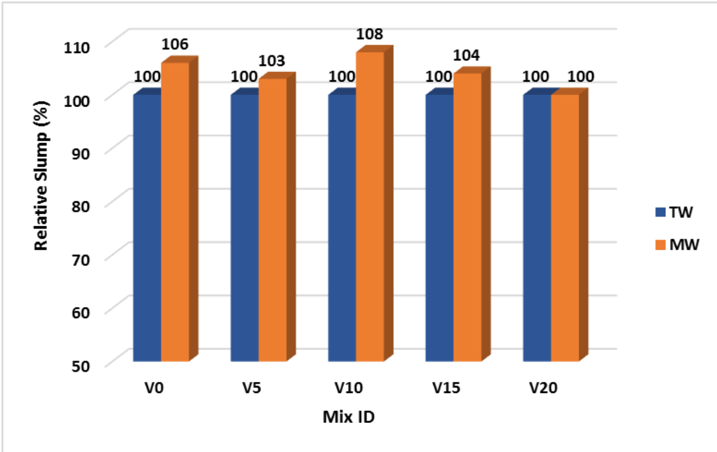


Figure 8. Effect of magnetized water on volcanic concrete slump.

3.3. Compressive Strength Test

Table 8 and Figure 9 show the compressive strength results of volcanic concrete made with TW (Group-1). As shown, the compressive strength of volcanic concrete increased at any VA content up to 15% VA. At 20% VA content, the compressive strength was similar to or less than that of volcanic concrete with no VA. At 5%, 10%, and 15% VA, the compressive strength increased by 24%, 8%, and 3%, respectively, at 7 days; increased by 18%, 11%, and 5%, respectively, at 28 days, and increased by 16%, 8%, and 3%, respectively, at 120 days. With using 20% VA, the compressive strength decreased by 5.5%, 0.0%, and 2% at 7, 28, and 120 days, respectively. The best result of compressive strength was achieved at 5% VA content. The compressive strength increases then decreases when increasing the VA content in volcanic concrete and this might be attributed to the fact that volcanic ash reacts with the calcium hydroxide produced from the hydration process, generating CSH gel, and therefore, the amount of CSH increases [38]. Figure 10 shows SEM images of volcanic concrete fracture surface made with TW and having 0% or 5% VA. By decreasing cement content at high ratios of VA, the calcium hydroxide decreases and hence the possible generated CSH decreases which adversely affects the compressive strength.

Table 8. Compressive strength values of volcanic concrete.

MIX ID (Group-1)		V0T	V5T	V10T	V15T	V20T
Compressive strength (MPa)	7 days	37	46	40	38	35
	28 days	44	52	49	46	40
	120 days	60	70	65	62	58
MIX ID (Group-2)		**V0M**	**V5M**	**V10M**	**V15M**	**V20M**
Compressive strength (MPa)	7 days	50	51	42	42	37
	28 days	54	58	52	50	43
	120 days	72	78	70	69	63

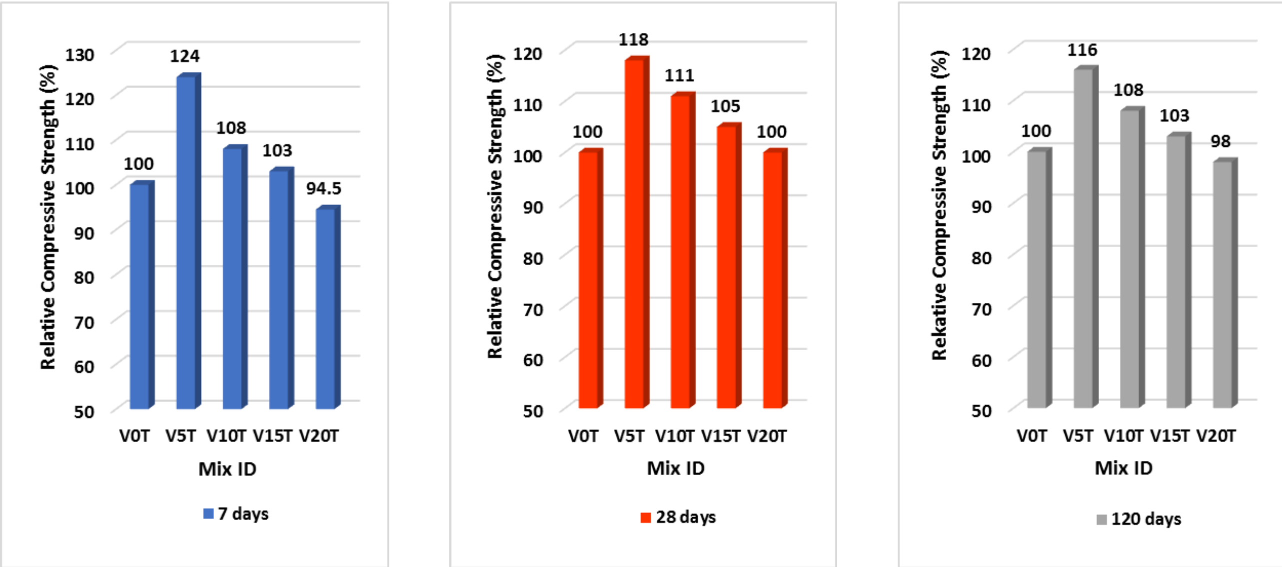
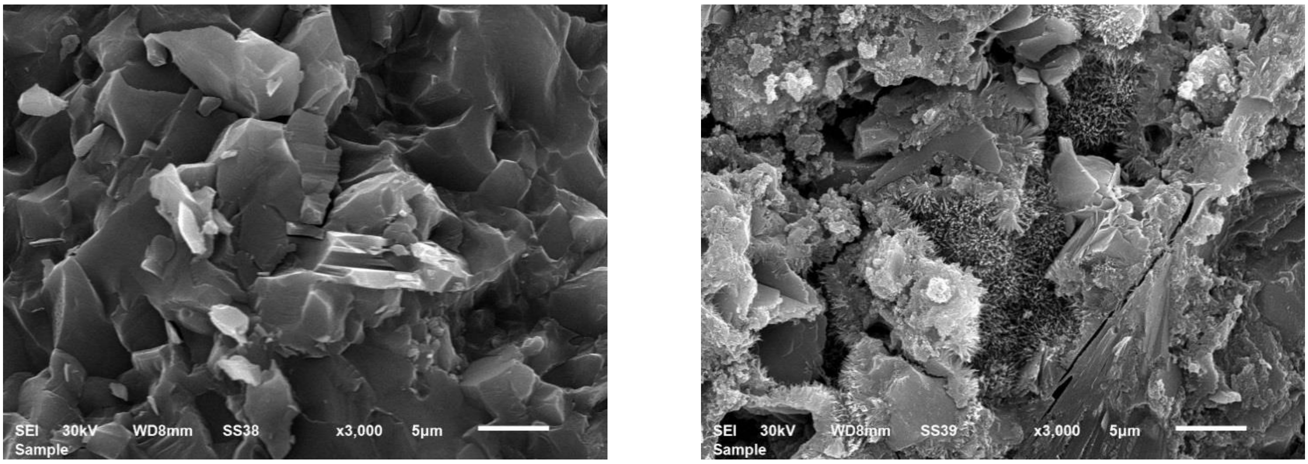


Figure 9. Effect of different ratios of VA on volcanic concrete compressive strength mixed with tap water.



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

Figure 10. SEM images of the fracture surface of volcanic concrete made with TW: (**a**) 0%VA and (**b**) 5% VA.

Table 8 and Figure 11 shows the effect of using MW in volcanic concrete with different ratios of VA. As shown, MW enhanced the compressive strength of volcanic concrete by different ratios. The compressive strength enhancement ranged between 5% to 35% at 7 days, 6% to 23% at 28 days, and 8% to 20% at 120 days. The best results were shown when no VA was used in the volcanic concrete. The positive effect of MW on the compressive strength can be attributed to effect of magnetic field on breaking large water clusters into smaller clusters or single water molecules. As a result, water activity increases, and more water is available for hydration. During the hydration reaction, the smaller water cluster or single molecules of magnetized water can easily penetrate the cement particles' core region through the thin layer of hydration products. This makes hydration process more effective and complete, which in turn generates more CSH gel and improves the compressive strength [18,23,25]. The effect of MW was relatively higher when no VA was used because the MW reacts only with cement particles and generates relatively more CSH gel and relatively less calcium hydroxide than that of when using TW [18,25]. Therefore, the total amount of CSH gel when using MW with the cement only is higher than that of when using MW with 5% VA as a replacement of cement. Therefore, the existence of VA reduces the positive effect of MW in enhancing the volcanic concrete compressive strength.

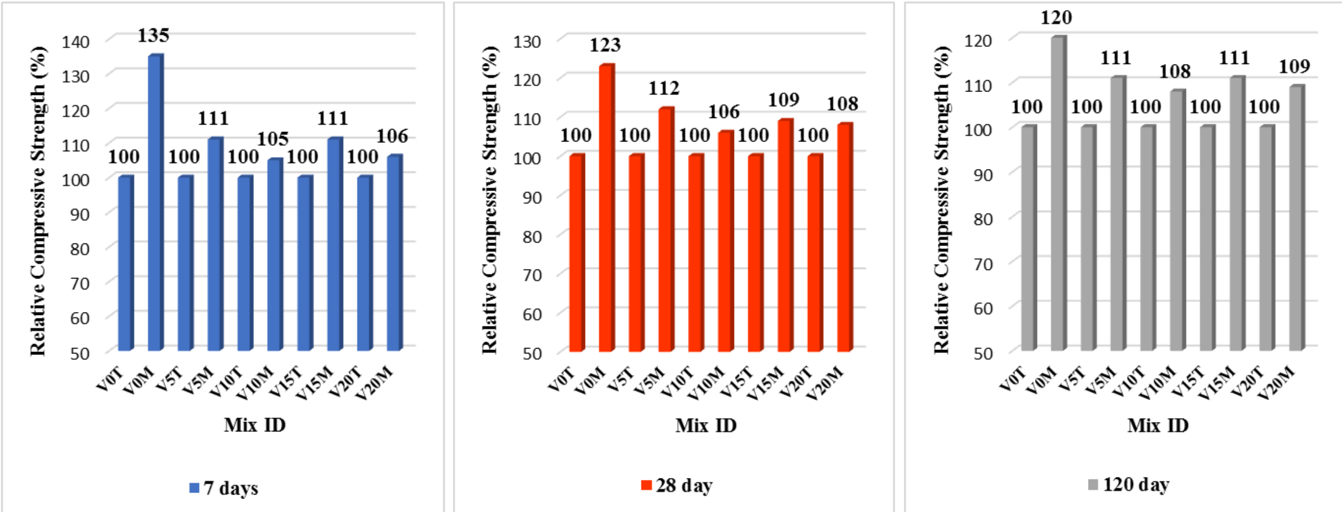


Figure 11. Effect of MW on compressive strength of volcanic concrete at 7, 28, and 120 days.

Figure 12 shows SEM images of the fracture surface of volcanic concrete made with magnetize water and having 0% or 5% VA. As shown in the figure and by comparing the effect of MW when used with 0%VA and with 5%, it can be clearly observed that the surface morphology is different between the two images in which the MW could disperse the water clusters and the corresponding cement particles more when no VA was presented, which caused better compressive strength. The MW effect on the volcanic concrete matrix/surface can also be seen by comparing the images in Figures 10 and 12, in which the presence of MW at any VA dosage could change the concrete surface morphology with more small and dispersed cement/VA particles.

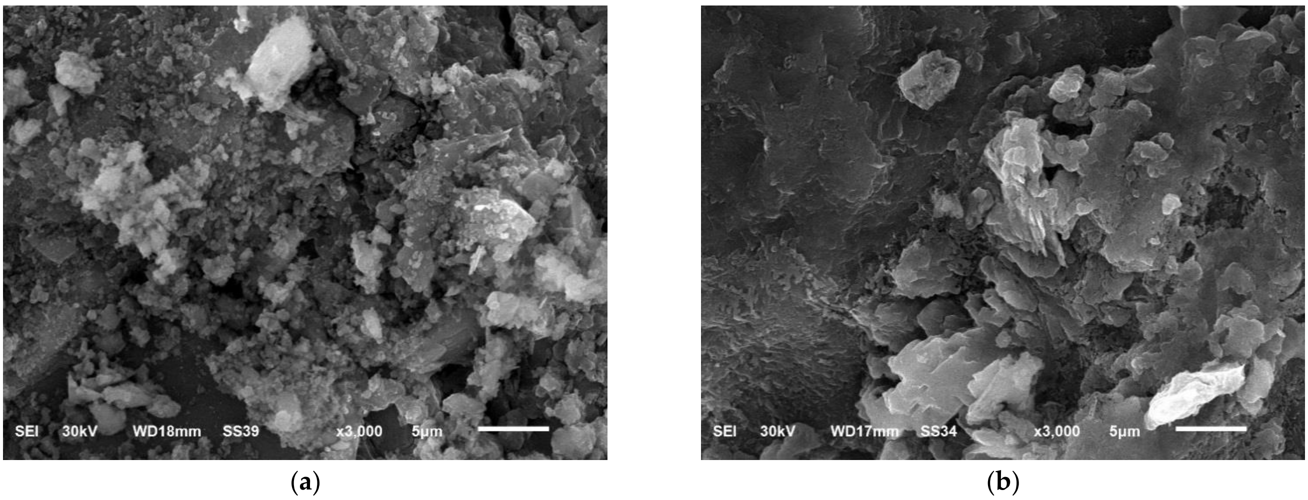


Figure 12. SEM images of the fracture surface of volcanic concrete made with MW: (**a**) 0%VA and (**b**) 5% VA.

Table 9 presents a comparison between the effect of MW on 28 days concrete compressive strength of some previous studies and the current study. From the table, it can be seen that the MW used in previous studies had different positive effects on concrete compressive strength that ranged between 3% to 18% compared with 12% strength enhancement in the current study. The value of compressive strength enhancement depended on the total binder and water to binder ratio in the mixes. By increasing the total binder content and decreasing the water to binder ratio, the effectiveness of the MW increased. Therefore, it can be concluded that the strength enhancement ratio occurred in this study is within the range observed in previous studies. However, the current study introduces an eco-friendly concrete type.

Table 9. Comparison of the effectiveness of MW in current and previous studies.

References	Mixture Contents (Kg/m^3)							W/B	Compressive Strength Enhancement (%)
	C	S	CA	MW	PM	SP	TB		
[39,40]	395	780	230	146.2	LP (210)	6.7	605	0.24	18
[41]	355	780	230	146.2	SF (39)	8.0	394	0.37	3
[42]	385	633	1155	180.9	–	–	385	0.47	10
Current study	475	586	1173	175.0	VA (25)	10.0	500	0.35	12

C: cement; S: sand; CA: coarse aggregate; MW: magnetized water; PM: pozzolanic materials; LP: limestone powder; SF: silica fume; VA: volcanic ash; W/B: water to binder ratio; SP: Superplasticizer; TB: Total binder.

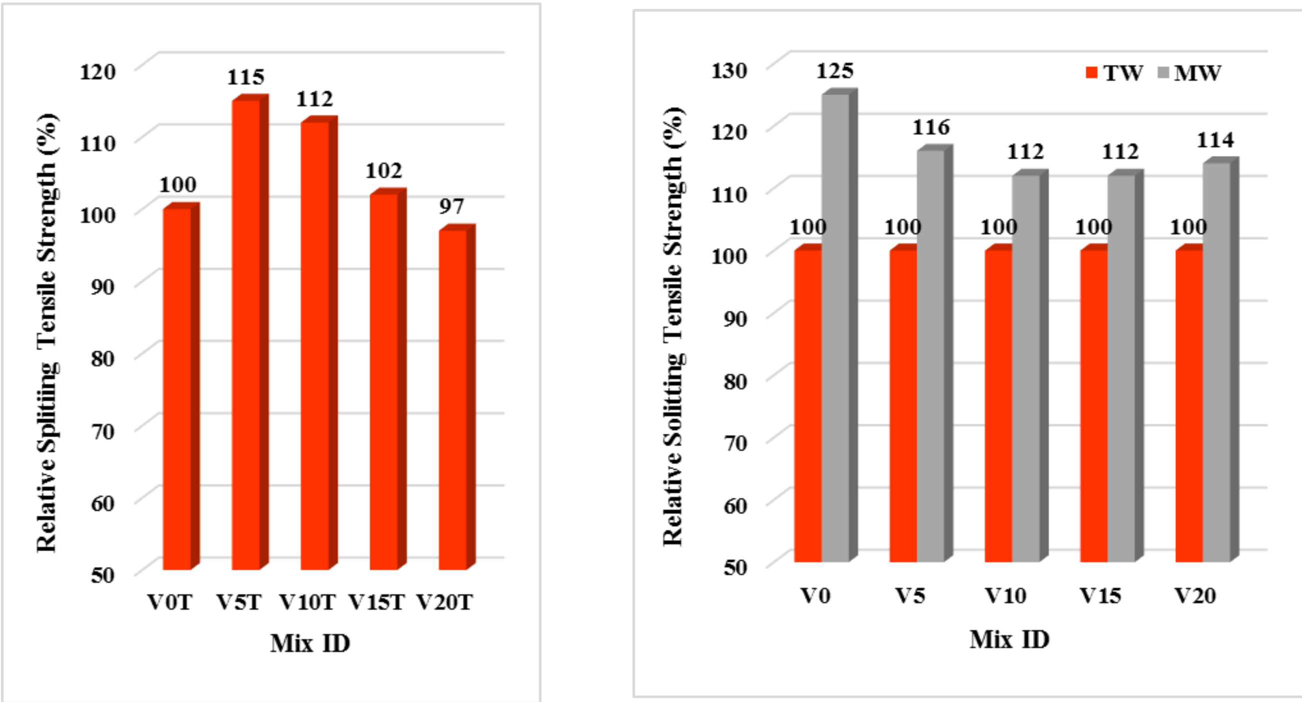
3.4. Splitting Tensile Strength and Flexural Strength Tests

Table 10 and Figure 13 show the 28 days splitting tensile strength results of volcanic concrete made with TW (Group-1) as well as MW (Group-2). As shown in Figure 13a, at any VA content up to 15%, the tensile strength was higher than that of the control mix V0T, similar to what occurred in its corresponding compressive strength. At 20% VA content, the tensile strength was less than that of volcanic concrete with no VA. At 5%, 10%, and 15% VA, the tensile strength increased by 15%, 12%, and 2%, respectively. When using 20% VA, the tensile strength decreased by 3%. The best result of tensile strength was achieved at 5% VA content. Figure 13b shows the effect of using MW in volcanic concrete with different ratios of VA on its tensile strength. As shown, MW enhanced the tensile strength of volcanic concrete by different ratios. The tensile strength enhancement ranged between 12% to 25%. The best results were shown when no VA was used in the volcanic concrete similar to what was observed in its compressive strength. The tensile strength behavior of volcanic concrete with and without VA or MW is attributed to the same reasons affected the corresponding compressive strength due to the strong correlation between them.

Table 10. Splitting tensile strength and flexural strength values of volcanic concrete at 28 days.

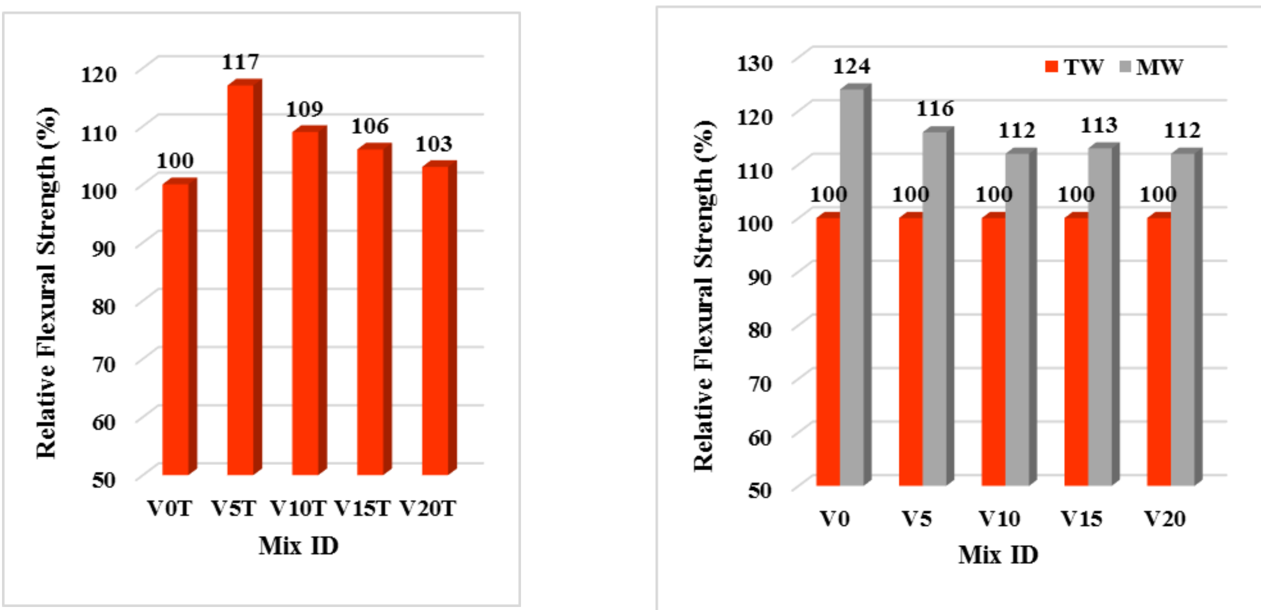
MIX ID (Group-1)	V0T	V5T	V10T	V15T	V20T
Splitting tensile strength (MPa)	3.82	4.40	4.30	3.90	3.70
Flexural strength (MPa)	8.70	10.20	9.50	9.20	9.00
MIX ID (Group-2)	**V0M**	**V5M**	**V10M**	**V15M**	**V20M**
Splitting tensile strength (MPa)	4.78	5.10	4.80	4.35	4.20
Flexural strength (MPa)	10.75	11.80	10.60	10.35	10.10

Similar to its splitting tensile strength, the flexural strength of volcanic concrete increased by using VA and MW at any VA content as shown in Table 10 and Figure 14. At 5%, 10%, 15%, and 20% VA, the flexural strength increased by 17%, 9%, 6% and 3%, respectively, as shown in Figure 14a. The best result of flexural strength was achieved at 5% VA content. Figure 14b shows the effect of using MW in volcanic concrete with different ratios of VA on its flexural strength. As shown, MW enhanced the flexural strength of volcanic concrete by different ratios ranged between 12% to 24%. The best effect of MW was shown when no VA was used in the volcanic concrete. The flexural strength behavior of volcanic concrete with and without VA or MW is attributed to the same reasons affected the corresponding compressive strength due to the strong correlation between them.



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

Figure 13. Volcanic concrete splitting tensile strength: (**a**) effect of VA and (**b**) effect of MW.



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

Figure 14. Volcanic concrete flexural strength: (**a**) effect of VA and (**b**) effect of MW.

4. Conclusions

This research focused on investigating the effect of magnetized water treated in a magnetic field of 1.4 T on the properties of volcanic concrete with different ratios of volcanic ash (0% to 20%) as a partial replacement of volcanic concrete cement. Two groups of volcanic concrete were made: one with using tap water and the other one with using magnetized water. The effect of water magnetization on its physical and chemical properties was also measured. As per the results of this research, the following conclusion could be drawn:

- Water magnetization increased its total dissolved solids value by 17%, increased its pH by 15%, decreased its surface tension by 7%, and did not affect its density;
- Using 5% VA showed the best results in all measurements when used in volcanic concrete with and without using magnetized water, regardless the age of concrete;
- Using VA in volcanic concrete decreased its slump when no magnetized water was used. However, the magnetized water was able to increase the volcanic concrete slump by up to 8%;
- The compressive strength of volcanic concrete increased by 24%, 18%, and 16% at 7, 28, and 120 days, respectively, when using 5% VA without using magnetized water. The compressive strength slightly decreased by up to 5.5% when 20% VA was used, compared with the control mix;
- The compressive strength increased by 35%, 23%, and 20% at 7, 28, and 120 days with no VA while the magnetized water was presented. The compressive strength increased up to 12% after 7, 28, and 120 days with 5% VA when magnetized water was utilized;
- Both splitting tensile strength and flexural strength of volcanic concrete with and without VA or MW behaved similar to that of the corresponding compressive strength.

Overall, the main advantage of using magnetized water in volcanic concrete is the enhancement of its fresh and hardened mechanical properties, especially when used with 5% volcanic ash as cement replacement. The enhancement in volcanic concrete workability by using magnetized water can also help in reducing the demand of superplasticizer in concrete which produces eco-friendly concrete with a relatively low cost.

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