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Review

Properties of Portland cement concrete cast with magnetized water: a review

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ABSTRACT

The water utilized in concrete manufacture plays an important role within the concrete mix, beginning from controlling the process of hydration of cement, besides appropriate curing to achieve the required strength, not to mention controlling the workability and durability of the concrete structure. The utmost significant challenge for concrete technology is to improve the properties of concrete. Nowadays, the engineering field needs to produce structures in harmony with the concept of sustainable development through the utilization of high-performance materials with an eco-friendly impact that is produced at a low-cost. The magnetic water (MW) provides one of the utmost towards this objective. The cost of magnetizing water is low because of the simple instruments used and the cost can be adapted to the scale of the work. In the last two decades, a new technology, so-called MW technology, has been extended to use in concrete manufacturing. Therefore, currently, the researchers are interested in the use of MW in the manufacture of cementitious materials helping to rationalize the cement usage and reducing reliance on chemical additives that have a negative environmental impact. Consequently, this paper presents the effect of the magnetization process in the structure of water molecules, the main properties of water. Additionally, the effect of using MW on the fresh and mechanical properties, as well as the durability characteristics and performance of cementitious materials have been reviewed. Moreover, the factors that affect the magnetization process of water, which highlighted discuss in this study. The results revealed that using MW significantly enhances the flowability and the characteristic strengths of cementitious materials as well as the durability properties.

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1. Introduction

Water is an important constituent of cement concrete as it actively participates in the chemical reaction with cement (Shetty, 2005). It plays a vital role not only in the hydration process of cement, but concrete fresh properties, hardened properties, microstructure, and overall durability properties of concrete as well. Water used for manufacturing as well as curing of concrete should be clean and free from any other contaminations that may be led to undesirable performance to cement or steel in concrete. Generally, the water used for making and curing the concrete is drinkable water except for the biological requirements (Goel and Kumar, 2014).

Water consumption is rising with population growth and inhabitants needs. The industrial sector comes in second place with 20% water consumption after the agricultural sector which accounts for 70% of water use (UN-Water Statistics, 2014). In concrete production practice, there are more than one billion tons of water consumed each year (Pang and Zhu, 2013). Since it is considered the lifeline, it should be rationalizing its consumption and maximize the use of it, and the use of Magnetic Water (MW) in various fields seeks to do so.

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In October 1993, the government of the Russian issued a Federal Program, in which applications of MW were recommended (State Construction Committee of Russia, 1993; Tkatchenko, 2004). These applications were not limited to the construction industry but included potential benefits in the domains of health, energy savings, and agriculture applications, among others. This recommendation was the basis for research work to take place in Russia and elsewhere to explore the potential merit in economization on cementing and ferroconcrete reinforcement, enhancing concrete performance, increase the life of constructions which, in its turn, lead to reducing corresponding construction costs.

The use of MW has been increasing in the applications and fields due to the development of magnetic devices. By using a permanent magnet, the magnetization process of water is simple to apply in concrete mixing plants, and economic method regarding the energy consumption if compared to using electromagnets (Esmaeilnezhad et al., 2017).

The target of this review study is to collect and compare the previous researches in MW concrete field as there are many merits of using this technology in concrete manufacture and to be a good reference to the researchers as there is still a need for more researches in that field. Despite, comprehensive data are available on the fresh and hardened properties of concrete when made with MW at various levels, the data are particularly scarce when it comes to durability and long-term effects of this relatively new concrete manufacturing approach.

2. The Role of Magnetization in the Structure of Water Molecules

Water chemistry (mineralogy, types of ions present, total dissolved solids, pH, etc.) is a key factor in concrete production that affects the mechanical properties of concrete, mainly its compressive strength, flexural strength, water absorption, workability, and durability (Hover, 2011; Wei et al., 2017). MW can be produced when Regular Water (RW) passes through a magnetic field with relatively slow velocity. When that happens, some definite changes occur in its molecular, mechanical, physical, electromagnetic, and thermodynamic properties compared to RW (Esfahani et al., 2018; Harsha, and Sruthi, 2018). The molecules of RW are not separated due to the existence of hydrogen bonds. The water molecules tend to be attracted to each other, forming clusters. Meanwhile, RW passes through or in the vicinity of a magnetic field, the size of these clusters and the number of grouped molecules declines (Zhou et al., 2000; Esmaeilnezhad et al., 2017). Moreover, the magnetic fields weakened the clusters' hydrogen bonds, diminishing the larger clusters and forming smaller ones with stronger hydrogen bonds (Toledo et al., 2008; Reddy et al., 2014a; Jain et al., 2017). Australian Fluid Energy, (1996) reported that the molecule clusters of MW have a lower degree of consolidation, and the volume of molecules is more uniform if compared with those of RW. Additionally, Harsha, and Sruthi, (2018) attribute the speed, ease completeness of the cement hydration process when using MW to the following reason. By passing the water through a magnetic field, the water molecules will lose their attractive and repulsive forces and then will be reoriented, and the neutralized molecules of water are more easily attracted to the electrostatic fields which naturally contained by cement grains. The effect of the magnetic field on water molecules is schematically shown in Fig. 1 (Taghried et al., 2017). As is observed, Fig. 1(a) illustrates water molecules arrangement in normal temperature. Water molecules tend to form clusters with hydrogen bonds, while these clusters are disintegrated due to the applied magnetic field as shown in Fig. 1(b).

It also has been confirmed by using the light spectrum that, the bond angle decreases from 104.5° to 103° due to the exposure to the magnetic field, which deflects and squeezes the bond pairs to be closer together as shown in Fig. 2 (Reddy et al., 2014a). Moreover, Taghried et al. (2017) reported that the structure of water is aligned in one direction after magnetization, and the molecule sizes change after the bond angle changes, penultimate, viscosity and surface tension decreased by magnetization, and eventually the hydration rate increases. Due to the smaller size of MW molecules, the water layer surrounding the cement is thinner than RW molecules, therefore less water demand will be required which has merits for hardened concrete properties. There are many researchers who confirmed the effect of the magnetic field in improving hydrogen bonding (Inaba et al., 2004; Cai et al., 2009).

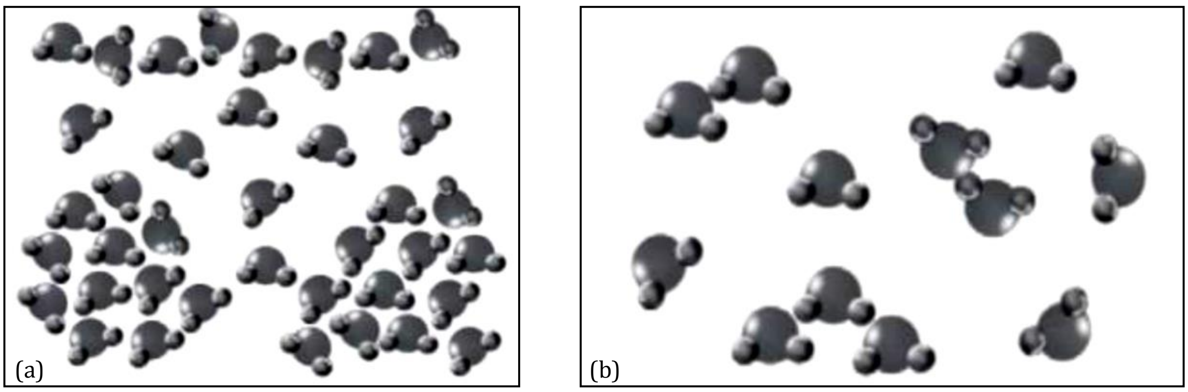

Fig. 1. The effect of the magnetic field on water molecules:
(a) Before magnetic treatment; (b) After magnetic treatment (Taghried et al., 2017).

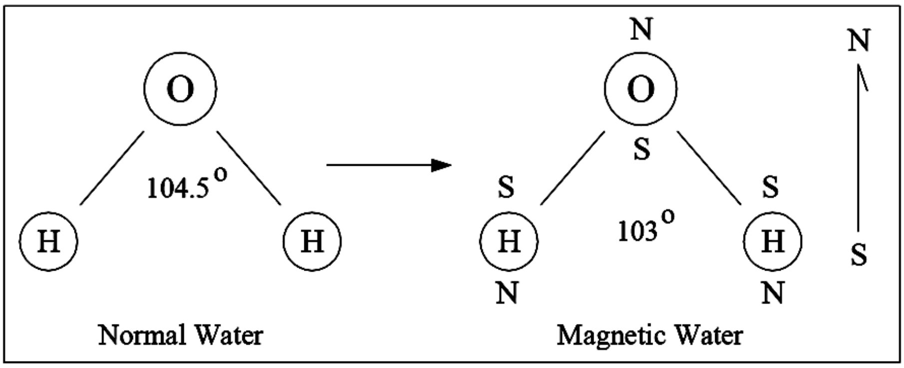

Fig. 2. The decrease in bonding in MW molecule (Reddy et al., 2014a).

By mixing the water and cement, the hydration process will firstly take place on the surface of the cement particles. Therefore, a thin layer of hydration products is created on the cement particles, which obstruct the further hydration of the cement particles. This action will obstruct the rate of gaining mechanical strength (Su et al., 2000; Jain et al., 2017). On the other hand, using MW decreases the accumulation of cement particles and helps the water molecules to penetrate more easily into the cement particles. Therefore, the hydration process will be done proficiently, which in its turn improves the mechanical properties of concrete (Nan and Chea-Fang, 2003; Jain et al., 2017; Wei et al., 2017; Gholhaki et al., 2018). Furthermore, Wang et al. (2011b) attributed the ease of MW penetration to cement grains to the loose connection between single polar molecules (O-2 and H+) and the water molecules. There are also other merits of incorporating MW into the concrete. Firstly, it improves durability properties; it also reduces or may prevent the use of chemical admixtures to increase compressive strength (Jain et al., 2017). Chau (1996) and Afshin et al. (2010) also reported that using MW decreases the amount of cement that is used to produce concrete mixes by about 5%, and it can also prevent the freezing of concrete mixes. Taghried et al. (2017) also concluded that cement content can be reduced up to 75 % without affecting compressive strength by using MW in concrete. In the same direction Afshin et al. (2010) determined that, with the same slump and compressive strength, cement content could be reduced by 28% in the case of magnetic concrete. Additionally, Al-Maliki et al. (2020) concluded that MW can be used to decrease the cement content up to 7.5% without affecting the concrete strength and workability. Thus, using MW in concrete certainly has a good environmental impact.

3. The Effect of Magnetization Process on Water Properties

MW has different mechanical, electromagnetic, and thermodynamic properties compared to RW (Esfahani et al., 2018). Joshi and Kamat, (1966) studied magnetic field effect on hydrogen bonds between water molecules and found some changes in the properties of water such as light absorption, surface tension, and pH value. For instance, bypassing the water through a 1.0 Tesla magnetic field in a circulation process for one hour and measuring the pH value every 10 min, Srinidhi et al. (2019) found that the pH value rose from 6.68 to 7.87 after one hour. Moreover, the permanent hardness of water ($CaCO_3$) also reduced from 450 to 365 mg/l due to the magnetization of water. Furthermore, the total solids, sulfate, and chloride content are declined from 700 to 500 mg/l, 800 to 690 mg/l, and 420 to 330 mg/l, respectively. However, Kumar and Krishna (2017) observed that the total hardness of water declined, and the total dissolved solids raised by increasing the number of hours of magnetization. It was also observed that pH value decreased from 7.8 to 7.1 after 96 hours of retaining water in a glass beaker over a circular magnet of 985 Gauss.

Bypassing the water through a 330mT magnetic field at a constant speed of 1.0m/s, Wang et al. (2011a) found that the pH value of ordinary water slightly increased from 7.52 to 7.61, which makes the water more suitable for use in concrete. Moreover, using a permanent magnet with 1 Tesla magnetic field and with a water flow of 1.32 m/s, Bharath et al. (2016) found that the surface tension of the RW was declined by 7.77% after magnetization and its viscosity declined by 6.8% and there was also a neglected rise in pH value as it is shown in Table 1. Additionally, Faris et al. (2014) found that the molecules of MW have a lower surface tension than RW, which leads to a higher activity of the cement particles in the mix. The effect of passing the water through a 260 Gauss magnetic field by 280mm length has been examined by Wei et al. (2017). It was found that the water surface tension declined by magnetic field by about 4.6%. It was also found that the conductivity of water increased by magnetization.

Table 1. Effect of magnetization on properties of water (Bharath et al., 2016)

Test parameter	Test results	
	RW	MW
Surface tension (N/m)	0.07275	0.06750
Viscosity (m^2/s)	7.65×10^{-6}	7.13×10^{-6}
Electrical conductivity (μs/cm)	343.20	353.30
pH	8.10	8.15

4. Methods of Magnetization

There are many methods for magnetization of water, which all are very simple and economic without any complication, which shed light on the ability to apply these techniques in ready-mixed concrete plants. The most popular method is allowing the water to flow with relatively low velocity in the vicinity of a magnet or through it (Hui, 1983; Joshi and Kamat, 1966). That can happen once only or passing the water several times to reach the required magnetization level. In the second method, a magnet is placed in the water container for a certain duration to reach the desirable level of magnetization. Some researchers reported that may contaminate the water with corrosion debris when the iron is used (Tkatchenko, 2004). Another method, glass containers are filled with water and then placed on a north pole or a south pole of a round magnet for a certain period, after that water can be used in the concrete industry and for better results, it can be used half of the water treated with a north pole and the other half treated with a south pole (Reddy et al., 2014a; Kumar and Krishna, 2017).

Any method of the previous ones required a magnetic field which can be achieved by either using permanent magnets or using electro-magnets (Sagar and Jawalkar, 2018). The permanent magnet creates a permanent magnetic field from the mutual alignment of the very small magnetic fields produced by every atom in the magnet from the spin and orbital movements of electrons (Saddam, 2008; Maeilnezhad et al., 2017). This method provides a permanent magnetic field with constant intensity without energy. On the other hand, the second method is to use electro-magnets, which produce a magnetic field by the motion of charged particles. It can be constructed from any coils of wire wrapped around a central iron core. Obviously, and unlike using a permanent magnet this method needs energy, but it provides various intensities by changing the current (Shivam and Sanjeev, 2017). There is maybe no evidence yet compared the effect of both magnets on MW.

5. Factors Affecting Magnetization

The magnetization field strength, the water velocity, contact time with the magnetic field, and the amount of exposing water to the field are viewed as the key factors that influence the water magnetization (Huchler et al., 2002; Abdel-Raouf, 2005). Moreover, Harsha and Sruthi, (2018) found that the level of magnetization is influenced by the method used and water purity.

5.1. Effect of the magnetic field intensity

Using a low magnetic field intensity (from 0.1T to 0.4T) seems to have a good effect on the properties of fresh concrete like slump and slump loss, however it has a tiny effect in the mechanical and durability properties of hardened concrete as it shown in the study of Abdel-Raouf and Abou-Zeid (2009). The fresh and hardened properties of self-compacted concrete raised significantly and gradually with the increase in the magnetic field intensity from 0.6T to 1.2T, but, using 1.5T have a lower value in the hardened properties only if compared with 1.2T (Jouzdani and Reisi, 2020). However, Venkatesh et al. (2020) investigated the effect using MW with 0.986T and 2T on the mechanical properties of concrete and the results indicated that the compressive, flexural, and splitting tensile strength have been all increased by approximately 15% for 0.986T intensity and 30% for 2.0T intensity if compared with RW concrete.

5.2. Effect of magnetic poles

Reddy et al., (2014a) studied the effect of magnetic field type i.e., North Pole (N), South Pole (S) and, mixed pole (N+S, half water exposed to the N and half exposed to the S) using normal and distilled water. The workability results of the slump for three different types of water: N, S, and N+S showed that in the case of the concrete made with a mixed pole (N+S) MW, the slump was slightly higher than other mixes, whilst the slump results of the control mix and the two other mixes (with N and S pole treated water) were the same. Additionally, the compressive strength results reveal that using mixed pole water increase the compressive strength significantly if compared with using one pole as shown in Table 2. Moreover, the slump results of using tap or distilled water were the same, whilst the distilled water achieved a mild increase in compressive strength in all cases. This increase in the strength is due to cluster concept of water and also memory of water concept. Generally, a water cluster consists of many water molecules of size 11–50, while the number of water molecules of MW decreases to a smaller amount of about the size 5–6 as the more water is available for hydration, the more number of cement particles are hydrated.

Table 2. Compressive strength of concrete samples at 28 days in MPa (Reddy et al., 2014a).

	Normal concrete	MW concrete		
		North	South	North & South
RW	28.29	41.50	38.01	44.06
Distilled water	30.64	42.92	40.91	45.02

5.3. Effect of magnetization process duration

To determine the effects of magnetization process time, Wang et al. (2013) reported that the hydrogen bonding between water molecules reaches a dynamic balance after a certain time under magnetization. After that, by increasing the magnetizing time, the balance slide toward weakening or even breaking the hydrogen bonding in water. Therefore, as the magnetizing time increases, the hydrogen bonding gets weaker, and the friction coefficient becomes lower. Another reason may be the water temperature, for the time that water passes through the water pump increases, a higher temperature is achieved. Therefore, the thermal motion of water molecules is known to become stronger, and thus hydrogen bonding weakens, as mentioned by (Jeffrey, 1997; Li et al., 2006). In addition, Ghorbani et al. (2018) passes the water through a 0.65 T permanent magnet at a constant speed and water flow of 2.25 m/s 10, 20, 40, and 80 cycles. The results showed that, passes the water 10 cycles gave the best results of the mechanical properties of concrete which confirmed the previous evidence. Furthermore, by filling glass beakers with water and placed them on round magnets (with 985 Gauss field intensity) for a different period namely: 24, 48, 72, and 96 hours, Kumar and Krishna (2017) found that the best time that gave the maximum enhancement in concrete properties was 72 hours. However, Reddy et al. (2013) used the same previous method for magnetization for different times from 1 hour to 72 hours and concluded that 24 hours of exposure to the magnetic field was found to be the optimum since after 24 hours the compressive strength of concrete was almost constant for all types of MW.

On the other hand, Yousry et al. (2020) studied the effect of the number of passing cycles through a magnetic field on the workability and compressive strength of cement mortar containing Fly Ash (FA). The results indicated that the optimum number of cycles was 150, 100, and 50 for mixes with 0%, 10%, and 20% FA as a partial replacement of cement, respectively. Hence, the more FA content, the less the number of magnetization cycles is required.

5.4. The effect of storage duration after magnetization

It has been reported that the magnetization effect on the RW can remain for hours or even for days after the magnetization process (Colic and Morse, 1999; Esmaeilnezhad et al., 2017). For instance, Nan and Chea-Fang (2003) and Afshin et al. (2010) confirmed that the MW can be stored in a reservoir up to12 h, after that its advantage may be lost.

Abdel-Raouf and Abou-Zeid (2009) passes the water through different magnetic field intensities (0, 0.1, 0.2, 0.3, and 0.4 T) and stored it for 3 days after magnetization and before mixing the concrete. The results showed that concrete mixtures that made with stored MW exhibited a lower slump if compared to the slump of the concrete mixtures made with un-stored MW. However, the slump values for the stored MW mixtures remained higher than those for the RW Mixture. All in all, these results revealed that mixes made with the stored MW generally provided lower strength. Thus, storing MW has a negative impact on compressive strength, slump, and slump loss.

6. Properties of Portland Cement Concrete Cast with Magnetic Water

6.1. Fresh properties

6.1.1. Workability

Many researchers reported that incorporating MW in concrete production increases the workability of concrete without increasing the Water to Cement ratio (w/c) or using plasticizers (Faris et al., 2014; Patil and Pathak, 2016). For instance, Gholhaki et al. (2018) reported that the use of MW instead of RW can enhance the flowability and viscosity of self-compacting concrete. Additionally, Bharath et al. (2016) demonstrated that the use of MW enhanced the workability of concrete mixes containing copper slag as a partial replacement of cement by about 50%. Reddy et al. (2013) also reported that water exposed to mixed pole (N+S) magnetic field will give good flowability with no sign of bleeding or segregation. Furthermore, using water treated by 0.8 T magnetic field in concrete helped to reduce the w/c ratio from 0.50 to 0.45 without using any additive to achieve a medium slump of 75 mm (Malathy et al., 2017). Moreover, Using MW, Taghried et al. (2017) found that the slump rocketed sharply by approximately 400%, 300%, and 25% for w/c ratios 0.45, 0.5, and 0.55, respectively compared with RW concrete mixes. Afshin et al. (2010) studied the effect of MW on the mechanical properties of high strength concrete incorporating plasticizers and concluded that beside the increase in the compressive strength of the concrete made with MW, which reached 18% more than those made with RW, the slump of the MW concrete was up to 45% greater than the slump of the control mixes. Additionally, it was concluded that passing the water only through the magnetic field gave a higher slump than passing the water and plasticizer solution. It has been observed that the slump of 1.0T MW concrete containing slag was 50% higher than RW concrete containing the same amount of slag. It was also observed that the MW helped to reduce the water content in MW concrete containing slag by 10-12% without any reduction in the slump (Bharath et al., 2016).

Additionally, Abdel-Raouf and Abou-Zeid (2009) found that the slump of the concrete mixture made with RW was mere 5 mm, whilst the slump of concrete mixtures made with 0.1, 0.2, 0.3, and 0.4 T MW rose significantly to 20, 70, 120, and 75 mm, respectively. Nevertheless, the relatively low slump of the 0.4 T mixture was attributed to a suggestion of the existence of an optimum value for the magnetization field intensity. A more recent study concluded that bypassing the water 150 cycles through a magnetic field, the consistency of cement mortar raised by approximately 33% while using 0.5% superplasticizer without using MW increased the mortar consistency by almost 40% (Yousry et al., 2020).

The increase in flowability of cementitious materials was attributed to the dispersion effect of MW on cementitious materials. Su and Miao (2003) also attributed the increase in the slump to the electrically charged water molecules due to magnetization, which has been thought to improve water interaction with cement in the fresh state.

6.1.2. Slump loss

In a large-scale study into MW concrete, Abdel-Raouf and Abou-Zeid (2009) observed the slump loss during a span of 90 min in the room temperature of 22°C to 25°C. Fig. 3 reveals the results of slump loss for concrete mixtures, made with a w/c ratio of 0.45 without admixtures. As is observed, incorporating MW in concrete provides a higher slump which gradually declined with time. It is also interested to note that the rate of slump loss increased with the increase of magnetic field intensity which may be due to the increase of hydration process rate with time. The large increase in the slump values prove that there are some merits for MW concrete, mainly for the concrete with plastic consistencies.

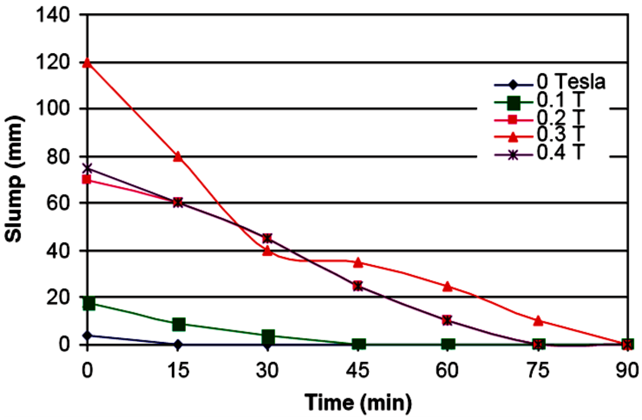

Fig. 3. Slump loss for concrete with 0.45 w/c ratio (Abdel-Raouf and Abou-Zeid, 2009).

6.1.3. Setting time

One study by Hassan (2008) examined the effect of MW on the initial and final setting time of cement mortars at early ages. The results showed that the use of MW reduced the initial setting time of cement mortar by 60% and 21.8% for w/c= 0.4 and 0.6, respectively compared with the use of RW. Additionally, the corresponding percentages of decreasing in final setting time of cement mortar were 19.2% and 19.6% for w/c = 0.4 and 0.6, respectively compared with the use of RW. Additionally, Soto-Bernal et al. (2015) found that the initial setting time of cement paste decreased by approximately 15-25% by using a magnetic field intensity of 19.1 and 25.4 Gauss, respectively. It is also concluded that there is a strong correlation between the magnetic field power and the setting time of cement paste; a higher power of the magnetic field decreases the setting time. Using MW reduces the accumulation of cement particles helping the water molecules to penetrate more easily into the cement particles. Therefore, the hydration process will be done proficiently, and rapidly which in turn reduces the setting time (Nan and Chea-Fang, 2003).

6.1.4. Unit weight and air content

Data related to the effect of MW on the unit weight and air content of concrete is very rare, so this point needs further research. Abdel-Raouf and Abou-Zeid (2009) concluded that MW whether incorporated immediately in concrete or after 3 days of storage did not seem to introduce a noticeable change in the unit weight or the air content of the concrete mixtures. The values of the air content are ranged from 1.5% to 3.7%, which may be higher with a tiny fraction than that for a non-air-entrained concrete.

6.2. Mechanical properties

As mentioned before the role of magnetization on the different properties of water such as, decreasing the surface tension and the viscosity, which, in its turn, decreases the accumulation of cement particles and also helps the water molecules to penetrate more easily into the cement particles. Therefore, the hydration process will be done proficiently, which eventually improves the mechanical properties of concrete.

6.2.1. Compressive strength

A considerable amount of literature has been published on the effect of MW on the mechanical properties of cementitious materials. Many investigations conducted confirmed that MW could raise concrete compressive strength which leads, normally, to increase flexural and tensile strength. Some research confirmed that MW could increase the compressive strength of concrete by a tiny fraction of 8%-10% more than RW concrete (Pang and Zhu, 2013; Taghried et al., 2017). Nonetheless, the vast majority of research affirmed that the MW could raise the concrete strength remarkably by approximately 8%-25% more than those mixed with RW. Afshin et al. (2010), Abed et al. (2012) and Faris et al. (2014), for instance, confirm that MW could rise concrete strength by about 10%-20% more than those mixed with RW. Moreover, Nan and Chea-Fang (2003) show that the compressive strength of concrete containing FA and prepared with MW raised by 15%-25% more than that prepared with RW. Likewise, Nan et al. (2000) achieve up to a 23% increase in compressive strength of concrete containing granulated blast furnace slag by using MW.

Additionally, Ghorbani et al. (2018) found that the results of a concrete mix made with MW (passes 10 times through 0.65 T magnetic field) displayed the highest rise in compressive strength with time compared to the control mix: about 38%, 21%, and 19% after 7, 14, and 28 days, respectively. This result reveals that the MW increases the early age strength by a higher proportion than the later ages, which confirmed also by Ghods (2014) who concluded that using the MW can improve the early-age compressive strengths of self-compact concrete mixes incorporating nano-silica. Moreover, Nan and Chea-Fang (2003) also observed 15% increases in 7-day compressive strength in MW concrete containing FA, and Bharath et al. (2016) also achieved a rise of 18% in 7-day compressive strength in MW concrete containing 15% slag as a cement replacement.

Moreover, recently Yousry et al. (2020) concluded that MW (passes 150 times through magnetic field) raised the compressive strength of cement mortar by about 10%, 25%, and 43% at 7, 28, and 56 days, respectively. Additionally, these results soared to 25%, 41%, and 62% at the aforementioned ages by adding 0.5% superplasticizers with the MW. In the same upward trend in the compressive strength of MW concrete, there are some researches affirmed that using the MW created a dramatic surge in compressive strength of concrete. Harsha and Sruthi (2018), for instance, concluded that despite there was a slight increase in 7-day strength, a substantial rise (roughly 58%) had seen in the 28-day strength of MW concrete compared with the RW concrete. Furthermore, Reddy et al. (2014b) concluded that by using MW the compressive strength of concrete rocketed by about 55% after 28 days and after 1 year the rise was about 51%. Kumar and Krishna (2017) also observed that the compressive strength of 72hrs MW concrete was 36% higher than that of RW concrete. Additionally, the compressive strength of 72hrs MW concrete increased by 29.44% and 28.27% in the mixes containing 15% FA and 2% Nano silica, respectively compared to RW concrete containing the same ratios of pozzolanic materials but made with RW.

Despite all the aforementioned research and its encouraging results, the results of Abdel-Raouf and Abou-Zeid (2009) indicated that there was some insignificant increase in 28-day compressive strength (mere 4-7%) by using 0.1 T MW in concrete, whilst by using 0.4 T MW the compressive strength dropped by about 26% compared to the mixture made with RW. Therefore, the author concluded that using MW propose no gain or rather some loss, in mechanical properties, particularly at 3 days. This result may be due to the low intensity of the magnetic field used in this research.

The wide range variation of the compressive strength results by using MW in concrete may be attributed to the aforementioned factors affecting magnetization such as the strength of magnetic field, the method used in magnetization, and the contact time with the magnetic field. Moreover, it is also opening the door to further study to reach any other factors that led to this dispersion in the results.

6.2.2. Flexural, tensile and bond strengths

The vast majority of the aforementioned researchers, who studied the compressive strength, studied also the flexural and tensile splitting strength of MW concrete which displayed better values if compared to RW concrete. Ghods (2014), for instance, concluded that using the MW can improve the tensile strengths of self-compact concrete mixes incorporating Nano silica. Additionally, Reddy et al. (2014a) concluded that tensile and flexural strength of concrete increased by 18% and 25%, respectively by using MW instead of RW for preparing concrete. Moreover, Kumar and Krishna (2017) also observed that the 3-days age tensile strength (splitting) and flexural strength of MW concrete were 13.29% and 23.94%, respectively higher than that of RW concrete. Bharath et al. (2016) studied the effect of using MW and slag on the mechanical properties of concrete, the experiments revealed that the split tensile strength and the flexural strength increased by 16.9%, and 10%, respectively over the RW concrete due to the synergistic effect of MW and 15% slag as a partial replacement of cement in concrete mixes. However, Abdel-Raouf and Abou-Zeid (2009) concluded that using MW has no effect on the flexural strength, and the tiny reduction that occurred in the modulus of rupture of MW concrete may be considered in the experimental allowed differences range.

Additionally, and recently, Wasim et al. (2020) concluded that using MW instead of RW increases the bond strength (between steel and concrete) of concretes with and without silica fume at different ages with different bar sizes diameters. For instance, by using only MW the bond strength increased by 15 to 21% at 28 days age depending on the bar size.

6.3. Durability properties

6.3.1. Water permeability

Considerable research results reveal that MW can make the hydration process of cement complete effectively, which, normally, can increase the cohesion and density of the concrete mixture and improve the compressive strength of concrete. So, it can infer that the permeability of MW concrete has been lessened.

Wang et al. (2011a) studied the water permeability of concrete samples with different strength grades C20, C25 and C30 made with and without MW with different magnetic field intensities (0.23, 0.28, 0.33 T) and different water flow rates (1m/s, 2m/s) under constant water pressure of 25 bar for 24 hours. It was found that all the depth of water penetration results of MW concrete are less than ordinary water concrete as is shown in Fig. 4. Moreover, among the range of test parameters, the best magnetic field which decrease the permeability to about half in all concrete grades, if compared with the ordinary water concrete, was 0.33 T with a water flow of 1m/s. That is to say, the permeability of concrete can decline with the rise of the magnetic field and the reduction of water flow through the magnetic field.

However, Abdel-Raouf and Abou-Zeid (2009) performed a water-permeability test by applying water at a constant pressure of 30 bars for 24h to concrete cylinders made with and without MW with different magnetic field intensities (0, 0.1, 0.2, 0.3, and 0.4 T). The results reveal that water magnetization has little influence on the results of permeability. The influence pattern was not well-defined. Moreover, there was a minimum negative effect of water storage for 3 days after magnetization and before incorporating into concrete. Finally, the author concluded that the reduction of w/c ratio is more effective in decreasing the concrete permeability than water magnetization.

6.3.2. Water absorption

Water absorption and density tests were conducted by Reddy et al. (2014a) for a concrete mix with tab water and other with mixed pole treated distilled water. The results showed that the concrete made with MW is exhibiting a 5% increase in density and about 32% reduction in water absorption if compared with tab water concrete. This is due to more hydration of cement due to the magnetic effect, which reduced the pores in the concrete. Likewise, the studies of (Reddy et al., 2014b; Gholhaki et al., 2018) reported an enhancement in the water absorption of concrete with MW. However, Ghorbani et al. (2018) concluded that the effect of MW on the water absorption of concrete block pavers was not noticeable. This result may be due to the high strength and density of the tested concrete block pavers, which originally have low permeability, so the effect of MW in reducing its absorption was not obvious.

However, Jain et al. (2017) found that there was an increase in water absorption by about 13% and 23% in samples prepared by MW which prepared by electromagnet of 0.8 and 0.9 T, respectively, whilst the absorption of the samples prepared by MW in 1.0 T was the same as the control ones. Moreover, the same trend occurred in the porosity test results.

The lower water absorption values of MW concrete may put down to the reduction of pores in the microstructure of those mixes. As mentioned before, as RW passes through a magnetic field, the activity of its water molecules increases. Consequently, the pore diameter in the microstructure of these mixes reduces due to the higher activity of MW molecules.

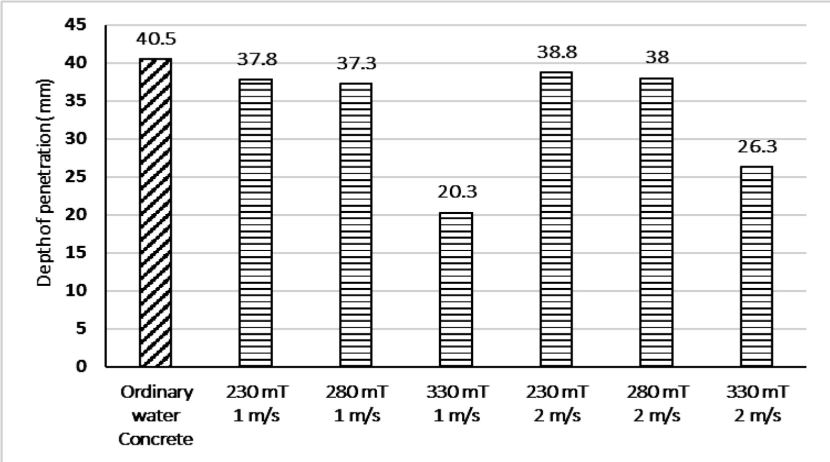

Fig. 4. Water penetration depth of C25 concrete (Wang et al., 2011a).

6.3.3. Sorptivity

The rate of water absorption by capillary suction into concrete provide valuable data regarding the pore structure, permeability, and durability characteristics of the concrete underexposure (Parrott, 1992a). Jain et al. (2017) studied the effect of MW on sorptivity of concrete made with and without MW with different magnetic field intensities (0, 0.8, 0.9, and 1.0 T). The results illustrated that using MW instead of RW and by raising the magnetic field intensity, the sorptivity of concrete declined as is shown in Fig. 5.

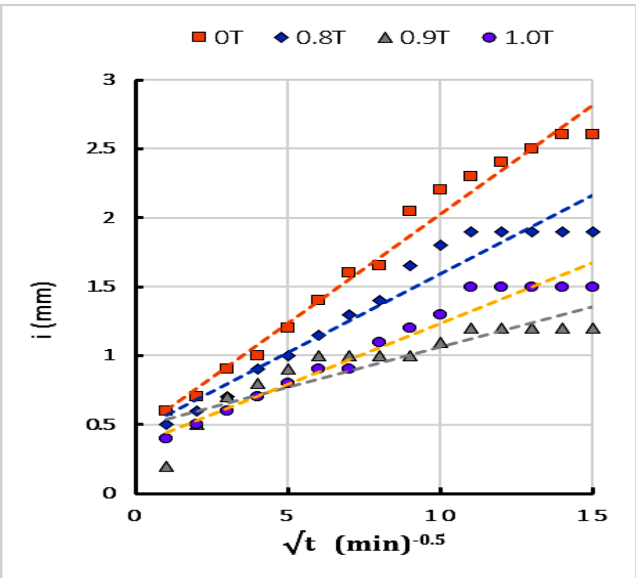

Fig. 5. Sorptivity of concrete samples made with MW with different magnetic fields (Jain et al., 2017).

6.3.4. Early-age shrinkage cracking

One of the most important durability aspects is the permeability of concrete, and the early-age shrinkage cracking of concrete is viewed as one of the main reasons that increase the permeability which in its turn leads to a decrease in the strength and an increase in the rate of deterioration with time.

The use of MW in concrete can improve early-age cracking resistance significantly. Wei et al. (2017) showed that the MW improved the early-age shrinkage cracking resistance of concrete mix compared to the specimens prepared with RW. By using a 260 mT magnetic field, the total cracking area of specimens decreases by 72.2%. Moreover, the shrinkage rate of concrete declined by using MW. For instance, the strain rate factor (α) of RW concrete is -140.02 while that of MW concrete is -112.11.

This result may be due to the reduction of the heat of hydration of cement and MW mixture, for Malathy et al. (2017) using 0.8 T permanent magnet measured the heat of hydration of cement and MW mixture according to ASTM C186, standard test method for heat of hydration of hydraulic cement, and the results proved that the heat of hydration of MW mixture was lower than that of RW. The cement mixed with MW, produces heat as 99.39 Cal/g, within the specified limits. This low heat of liberation reduces the thermal stress and prevent the cracks at early ages in concrete. However, Soto-Bernal et al. (2015) showed an increase in the rate and heat of hydration when magnetized water was used, pointing to in addition to the normal heat of cement hydration, there is also an additional temperature rise due to magnetostatic exposure, which is directly proportional to the strength of the magnetic field.

6.3.5. Rapid chloride permeability

The rapid chloride Penetration test was performed by Abdel-Raouf and Abou-Zeid (2009) according to ASTM C1202. It was concluded that the reduction in the total charge passed through different concrete samples made up with MW with different magnetic field intensity (0, 0.1, 0.2, 0.3, and 0.4 T), whether stored for 3 days after magnetization or add immediately to concrete, were relatively low if compared with the reduction due to decreasing w/c ratio without any magnetization. Therefore, according to Abdel-Raouf and Abou-Zeid (2009), it can be concluded that water magnetization does not lead to a noticeable impact in enhancing chloride penetration resistance of concrete.

However, Srinidhi and Navaneethan (2019) used a 1.0 T permanent magnet, which helps to increase the workability of concrete and lead to reduce the w/c ratio from 0.45, in RW concrete, to 0.3 to obtain the same slump range (50mm to 100mm). Therefore, the total charge passed declined from 3013 coulombs in RW concrete to 1782 coulombs in MW concrete.

Therefore, it can be inferred that the results of Abdel-Raouf and Abou-Zeid (2009) may be due to the low field intensity of the used magnet, and by increasing the magnetic field intensity, the better resistance to chloride penetration will be obtained. Moreover, the reduction in the total charge passed in the results of Srinidhi and Navaneethan (2019) may be due to the reduction in w/c ratio, which was done with the help of magnetization without affecting the workability of concrete.

6.3.6. Sulfuric acid attack

Sulfuric acid is particularly aggressive, for it not only attacks the aluminates phase, but it also attacks the Calcium Hydroxide $Ca(OH)_2$ or (CH) and Calcium-Silicate-Hydrate (C-S-H) which eventually leads to compressive strength loss and sequential spalling of the concrete surface (Nevil, 2011; Mohseni et al., 2017). Allahverdi and Škvara (2000) confirmed that sulfuric acid attack leads to extensive formation of gypsum in the regions near the surfaces of concrete and tends to cause high mechanical stresses that eventually lead to spalling and exposure of the next fresh surface.

In a study on concrete block pavers, Ghorbani et al. (2018) concluded that the blocks made up with RW have less resistance to sulfuric acid attack if compared with MW concrete blocks and had a mass loss of 10% after 120 days of exposure to 5% H_2SO_4 solution with pH 1.0, whilst the specimens with 10 times pass through a 0.65 T magnetic field had a mass loss of mere 5%. The mass loss of the concrete specimens was accompanied by a reduction in compressive strength by about 34% in normal concrete and nearly 23% in MW concrete as is shown in Fig. 6. This figure also confirmed that there is an optimum time of passing the water through the magnetic field to complete the magnetization process perfectly as aforementioned in section 5.2.

A chemical soundness test was performed by Abdel-Raouf and Abou-Zeid (2009) by exposing 50mm concrete cubes to saturated magnesium sulfate solution and 10% sulfuric acid. After a relatively short duration (8 weeks) of exposure to weekly cycles of wetting and drying the results indicated that the mixture made with RW exhibited 8% mass loss, whilst the mixture made with 0.1 T MW exhibited 1.2% mass loss as is shown in Fig. 7. The results of samples exposed to magnesium sulfates demonstrate a similar mass loss regardless of their magnetization field intensity.

The higher resistance of MW concrete to sulfate attack may be put down to the reduction of pores in the microstructure, as a result of their higher density and the greater degree of hydration. These results are in good agreement with the results of Ahmed (2017), who found a remarkable enhancement in the microstructural properties of concrete as a result of using MW instead of RW.

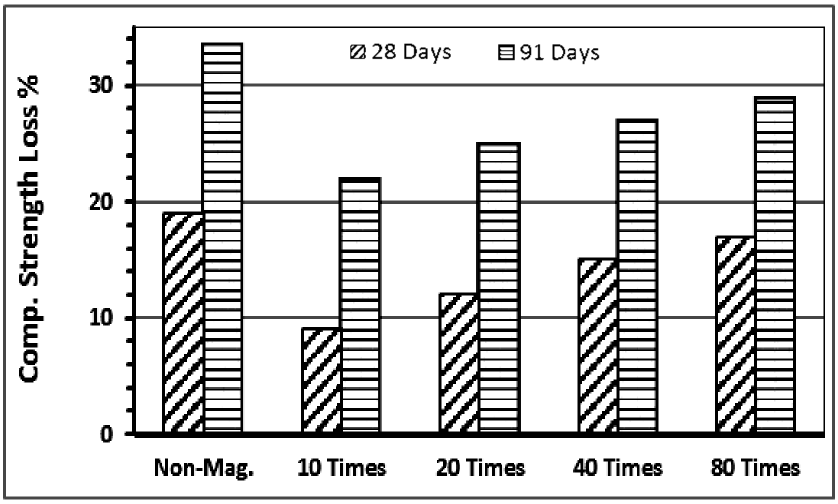

Fig. 6. Reduction in the compressive strength of concrete specimens exposed to 5% by weight of H_2SO_4 solution after 28 and 91 days of exposure (Ghorbani et al., 2018).

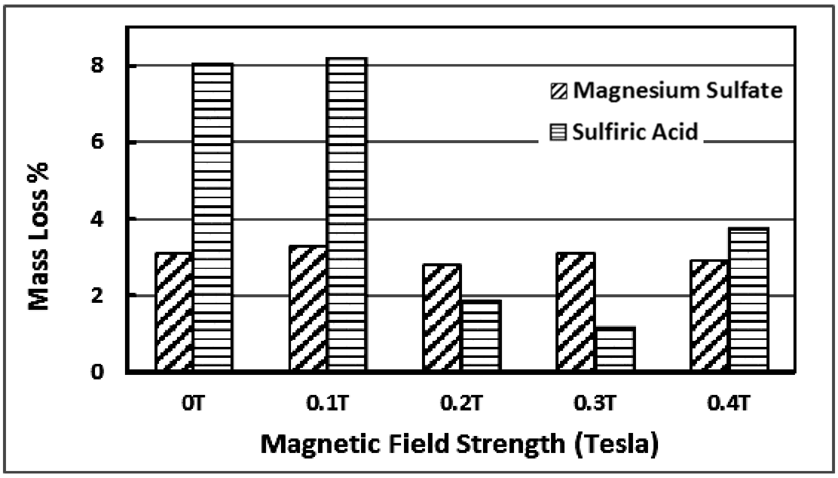

Fig. 7. Mass loss of concrete mixtures exposed to cycles of wetting and drying in sulfate solutions (Abdel-Raouf and Abou-Zeid, 2009).

6.3.7. Resistance to abrasion

Despite the importance of abrasion resistance, especially for the durability of concrete floors, sidewalks, there is fewer research work on it. Abdel-Raouf and Abou-Zeid (2009) investigated the abrasion resistance for 70×70×40mm specimens exposed to an abrasion rotation length of 500 m under 500 g/cm^2 stress and eventually, the specimen's weight loss was measured. The results indicated that the MW concrete has a higher abrasion resistance than RW concrete. For instance, the mixture made-up with 0.3 T MW exhibited lower than 1.2% mass loss, with more than 55% lower than that made-up with RW.

6.4. Microstructure of concrete

Scanning Electron Microscopy (SEM) can be used to understand the cause of the enhancement of the measured properties of cementitious materials. Many researchers (Wei et al., 2017; Ahmed, 2017; Esfahani et al., 2018) used this technique to evaluate the microstructure of the MW cementitious materials. Ghorbani et al. (2018), for instance, performed SEM on RW concrete and concrete made with water passed 10 and 80 times through 0.65 T magnetic field with a constant flow of 2.25 m/s as is shown in Fig. 8. From the provided images, it was observed that the microstructure of MW concrete is denser than that of RW concrete.

Moreover, Bharath et al. (2016) observed a concrete mix incorporating 15% copper slag, as a cement replacement, under the electronic microscope after 28 days. Fig. 9 shows the SEM image of concrete prepared with RW and 1.0 T MW. Bharath et al. (2016) observed that MW concrete contains more C-S-H crystals than RW concrete. It was also observed that CH crystals were smaller and separated in MW concrete. Figs. 10(a-b) present the SEM images of both 1.2 T MW and RW concrete, respectively all made with 2% nano alumina as a replacement to Portland cement. It was concluded from the images that a large amount of C-S-H and a lower number of pores were found in MW concrete in comparison with RW concrete (Ahmed, 2017).

Furthermore, Ahmed (2017) performed a desorption test on cement pastes containing (0%, 1%, 2%, 3% nano alumina) all made with and without MW. This test was used to estimate the number of interconnected pores (capillary porosity) as described by Young (1967), Parrott (1992b) and Ngala et al. (1995). It was found that using MW instead of RW led to a significant reduction in the capillary porosity of cement paste specimens made with MW over those made of RW reached about 33%, 36%, 47%, and 40% when 0%, 1%, 2%, 3% nano alumina replacement levels were adopted.

From these results, it can be inferred that using MW instead of RW provides a remarkable enhancement in the microstructure of cementitious materials, as cement reacts easily with the smaller molecules of MW leading to faster and complete formation of C-S-H.

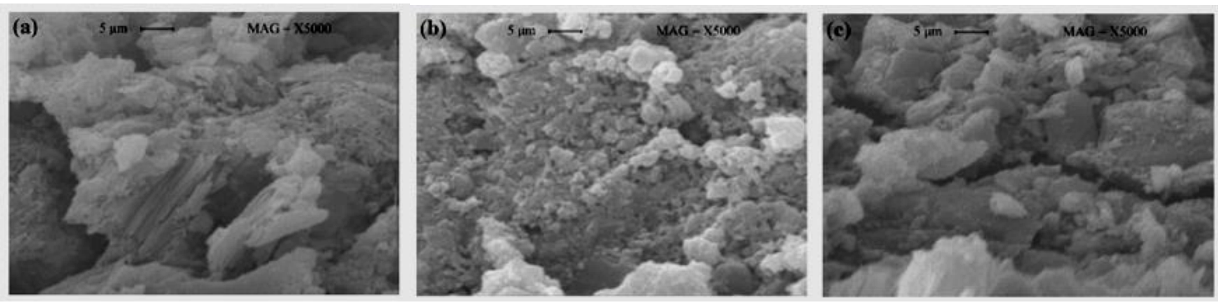

Fig. 8. SEM images (5000X) for concrete mixed with: (a) Regular water; (b) Water passed 10 times through magnetic field; (c) Water passed 80 times through magnetic field (Ghorbani et al., 2018).

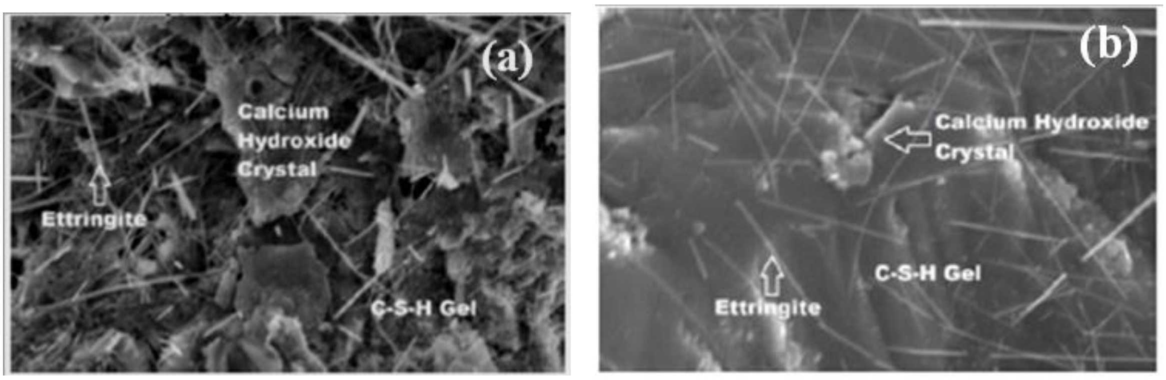

Fig. 9. SEM images (5000X) for copper slag concrete (15% replacement) mixed with: (a) Regular water; (b) 1.0 T MW (Bharath et al., 2016).

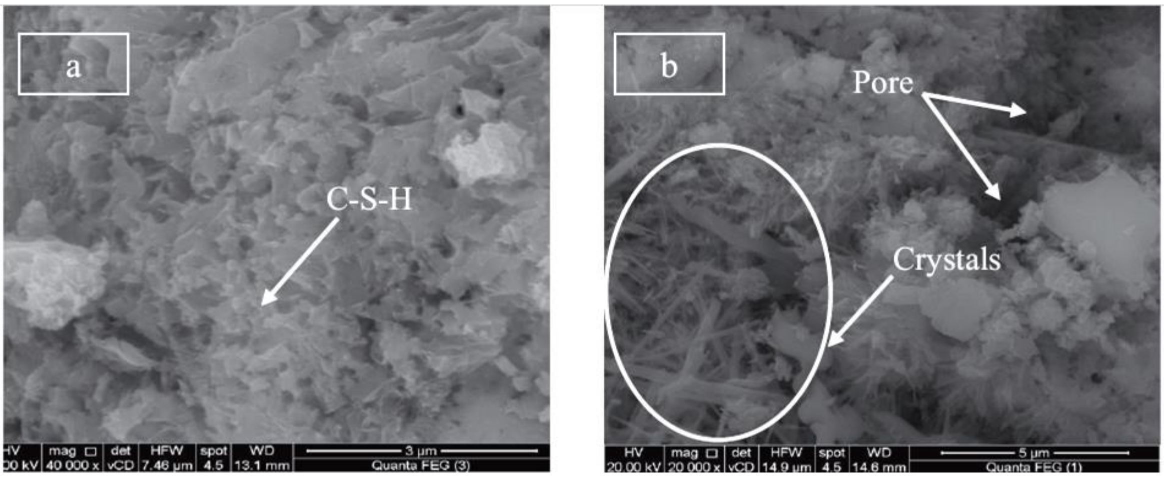

Fig. 10. SEM images for nano alumina concrete (2% replacement) mixed with: (a) 1.2 T MW (40000X); (b) Regular water (20000X) (Ahmed, 2017).

7. Applications

There are some applications which already made using MW concrete in Russia and exhibit a high performance compared to concrete made with RW after years of exposure to environmental conditions such as severe temperature change, humidity, salty, acidic environments, and mechanical loads as shown in the Figs. 11-13 (Magnetic Technology L.L.C. Website, 2020). Applying the MW technology in the practical and manufacturing processes of concrete is a very simple process and has valuable ecological merits, so through this research, it is recommended to increase the use and applications of this technology in the concrete industry..

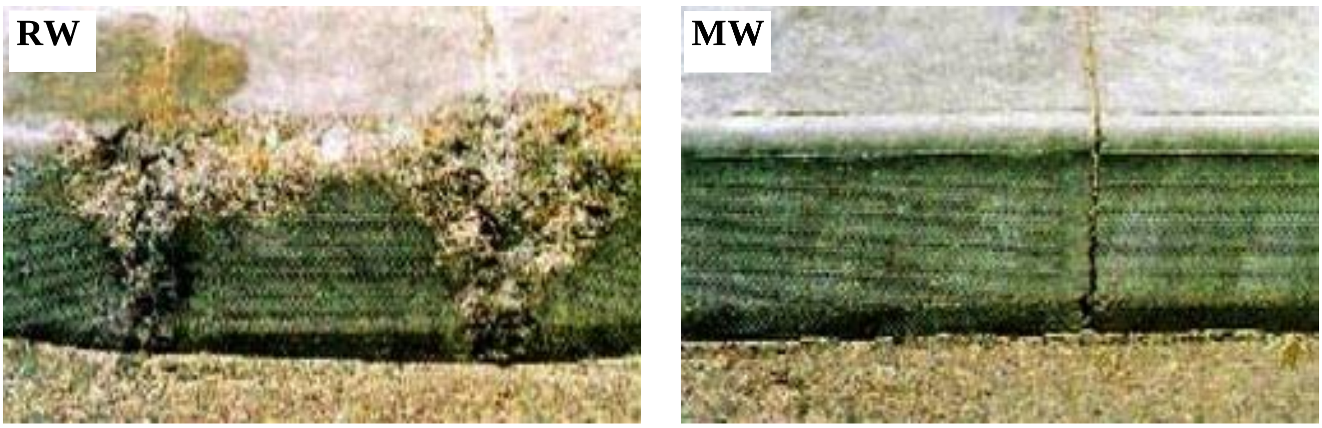

Fig. 11. Highway precast pavement, 3 years old. Rostov- Na-Donu, Russia (Magnetic Technology L.L.C. Website, 2020).

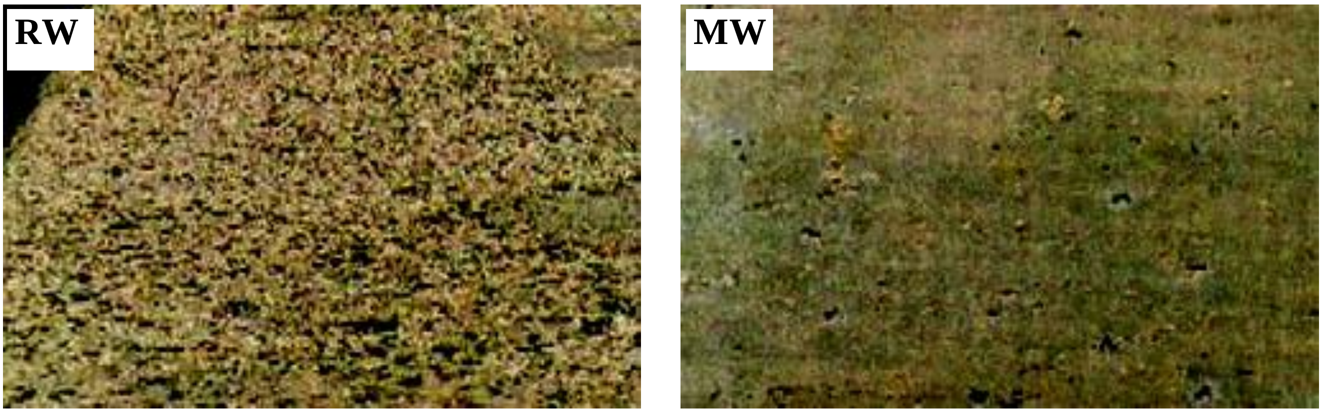

Fig. 12. Highway Concrete slabs after one year of exposure to a wide range of temperature changes (40°C to-40°C), Siberia, Russia (Magnetic Technology L.L.C. Website, 2020).

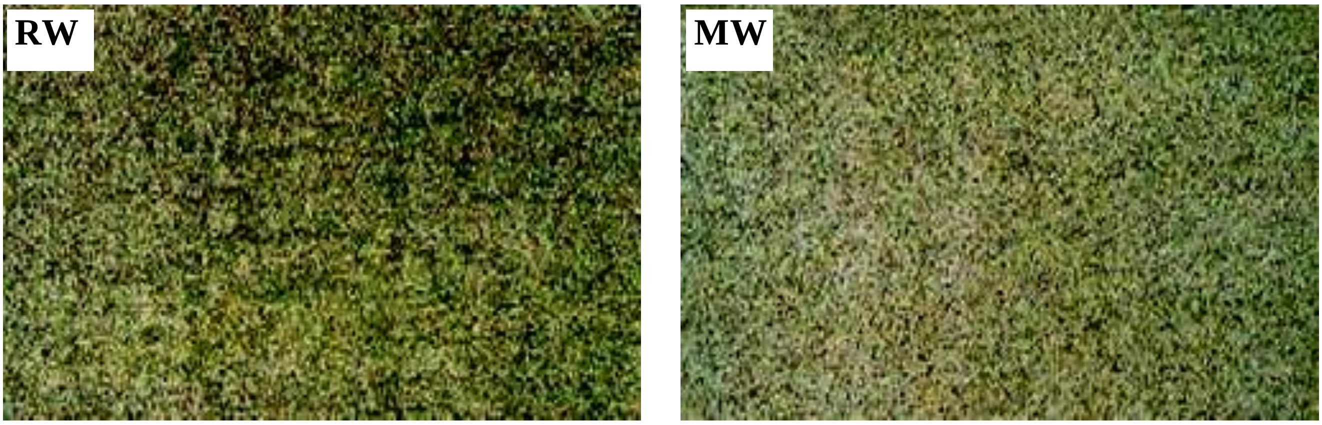

Fig. 13. Change in the structure of concrete pavements after 5 years of constructions, Moscow, Russia (Magnetic Technology L.L.C. Website, 2020)

8. Conclusions

Based on the results of the previous researches, the following conclusions and recommendations can be summarized:

- The magnetic fields weakened the water clusters' hydrogen bonds, diminishing the larger clusters and forming smaller ones with stronger hydrogen bonds. Additionally, the bond angle in the water molecule slightly decreases due to the exposure to the magnetic field.
- The magnetization of water for concrete production is done in simple and economical methods without any complications particularly when a permanent magnet is used, however, the water may take a longer time before mixing to reach the optimum degree of magnetization, which may take several cycles.
- Water magnetization leads to a tiny reduction (4.5% to 8%) in the surface tension and the viscosity of water and a mild rise in the pH value.
- Using a mix of water half exposed to the North Pole and the rest exposed to the South Pole leads to better results particularly in the compressive strength results than using all water exposed to one type of pole.
- There is a threshold for the time or the number of times water passes through the magnetic field depends on the magnetic field intensity and/or the flow speed of water through the magnetic field.
- The water magnetization process should be performed just before mixing, as storing MW leads to losing the magnetization effect and in some cases lead to a negative impact on the properties of the cementitious materials.
- Incorporating MW in concrete offers a higher flowability due to the dispersion effect of MW on cementitious materials which provides a better chance to reduce the w/c ratio, reducing the amount of admixture, and maximize the efficiency of cement in concrete mixtures. Moreover, most results prove that MW is more suitable for moderate concrete consistencies requiring little or no admixtures. Additionally, further researches are needed to study the effect of passing the water only through the magnetic field or passing the water mixed with the plasticizer solution.
- MW decreases the initial and final setting times, increased the early age shrinkage cracking, and has a neglected effect on the unit weight and the air content of the concrete mixtures. Further researches are needed in this point due to the fewer data available.

- The heat of hydration of hydraulic cement using MW needs further research as it is a point of argument noticed in the literature.
- Using MW leads to a remarkable rise in concrete compressive strength (8% to 50%) at 28 days age. However, some researches exhibit increases up to 7% in the compressive strength.
- MW concrete has a higher resistance to sulfate attack than RW concrete, and it helps to reduce the water permeability, absorption, and sorptivity of concrete, however, it has a neglected effect on the water permeability of high strength concrete or concretes with low W/C ratio.
- Likewise, the water permeability properties, water magnetization has a lower effect in decreasing chloride ion permeability than other indisputable factors such as decreasing w/c ratio.
- The use of MW enhanced the microstructure of concrete and lead to a denser microstructure than that of RW concrete, with a large amount of C-S-H and a lower volume of pores.

Eventually, there is a wide range in the results of the effect of using MW in the properties of concrete among the results of the different researchers, which is in some properties maybe reach to a paradox, that may be due to the many different factors that affecting the magnetization process which needs more further in-depth researches. Moreover, further researches needed to evaluate the effect of MW on the modulus of elasticity of concrete, setting time, unit weight, and air content of concrete mixtures, and mixing the superplasticizers with the water before the magnetization process. As well, there is a need to assess the use of MW in reinforced concrete elements and field applications.

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