EFFECTS OF MAGNETICALLY TREATED WATER ON PROPERTIES OF CONCRETE

by

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ABSTRACT

EFFECTS OF MAGNETICALLY TREATED WATER ON PROPERTIES OF CONCRETE

The aim of this thesis is to investigate the effects of magnetic field on water properties and the effects of magnetically treated water on concrete properties. For this reason a device was set up to prepare treated water. Permanent neodymium magnets were located around a PVC pipe and it was used to create treated water and admixture. To investigate the effects of magnetic field on water properties pH, Surface Tension, viscosity, FTIR and NMR tests were conducted. To determine the effects of magnetically treated water on concrete properties 32 concrete mixtures were prepared. The variables of concrete mixtures were the treatment of water, type of admixtures, treatment of admixtures and cement dosage. For 24 concrete mixtures the recipes were same. 4 concrete mixtures were produced without admixtures and 4 mixtures were produced at same workability level with different water/cement ratios. It was aimed to determine the effect of magnetically treated water on workability and strength of concrete. Also rapid chloride ion permeability test and water penetration under pressure test were carried out to investigate the influence of water treated by magnetization on durability of concrete. The experiments were conducted at Boğaziçi University Construction Materials Laboratory, Sabancı University Biochemistry and Nuclear Research Laboratory and Akçansa Cement Technology Center. Results showed that magnetization can change the properties of water such as increase in pH and viscosity, decrease in Surface Tension, change in hydrogen bond strength and decrease in size of water clusters. On concrete side, it was found that there can be an enhancement in workability of concrete when treated water or admixture is used and the improvement in workability can lead to a decrease in water amount used in concrete production and an improvement in compressive strength.

ÖZET

MANYETİK ETKİYE MARUZ KALAN SUYUN BETON ÖZELLİKLERİNE ETKİSİ

Bu çalışma, manyetik alana maruz kalan suyun özelliklerindeki değişimin ve bu suyun beton özelliklerine etkisinin araştırılması amacıyla yapılmıştır. Bu amaçla manyetik etki oluşturacak bir düzenek hazırlanmıştır. PVC boru etrafına neodyum mıknatıslar yerleştirilmiş ve borudan geçirilen su ve katkının manyetik etkiye maruz kalması sağlanmıştır. Manyetik alanın su özelliklerine etkisini tespit etmek amacıyla pH, yüzey gerilimi, viskozite, FTIR ve NMR analizleri yapılmıştır. Manyetik etkiye maruz kalan suyun beton karma suyu olarak beton özelliklerine etkisini araştırmak için 32 beton karışımı hazırlanmıştır. Karışımlarda suyun manyetik etkiye maruz kalması, katkının manyetik etkiye maruz kalması, katkı tipi ve çimento dozajı değişken olarak kabul edilmiştir. 24 beton karışımı aynı reçete ile hazırlanmıştır. 4 beton karışımında kimyasal katkı kullanılmamıştır. 4 beton karışımı ise farklı su/çimento oranlarında ve aynı kıvamda üretilmiştir. Ayrıca, manyetik etkiye maruz kalan su ile yapılan betonların dürabilite özellikleri de incelenmiştir. Bu kapsamda hızlı klorür iyonu geçirimliliği deneyi ve basınç altında su geçirimliliği deneyi yapılmıştır. Deneyler Boğaziçi Üniversitesi Yapı Malzemeleri Laboratuvarında, Sabancı Üniversitesi Biyokimya ve Nükleer Araştırma Laboratuvarlarında ve Akçansa Çimento Teknoloji Merkezinde yapılmıştır. Çalışma sonucunda manyetik etkinin suyun pH derecesini ve viskozitesini arttırdığı, yüzey gerilimini düşürdüğü, hidrojen bağ gücünü değiştirdiği ve bunun sonucu olarak su kümelerinin parçalanıp ebatlarının küçülmesine neden olduğu tespit edilmiştir. Beton deneyleri sonucunda ise manyetik etkiye maruz kalan suyun ve/veya katkının betonun işlenebilirliğini arttırabildiği ve bu sayede aynı kıvamı elde etmek için daha az su kullanılabileceği tespit edilmiştir.

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B	Magnetic induction
c	concentration
D	Diameter
e	Ion charge
F_L	Lorentz force
g	Gravity force
H	Shape dependent of water drop
I	Current
Q	Electric charge
t	Efflux time
T1	Spin-lattice relaxation time
v	Velocity of water flow
η	Viscosity
Δp	Pressure of water drop
τ_c	Correlation time
v_o	Frequency
γ	Gynomagnetic ratio

LIST OF ACRONYMS/ABBREVIATIONS

$FTIR$	Fourier transform infrared spectroscopy analysis
$H - NMR$	Hydrogen nuclear magnetic resonance
LS	Lignosulphonate
NS	Naphtalene sulphonate
$O - NMR$	Oxygen nuclear magnetic resonance
P	Polycarboxylic ether
ST	Surface tensionSurface tension
VC	Vinyl copolymer

1. INTRODUCTION

Concrete is the most used construction material all over the world because of its advantages in production, mobility and cost. For quite some time, concrete has been produced at plants by the automation systems and this product is called “ready mixed concrete”. Today, concrete production takes place in full automated plants in many countries. The first ready mixed concrete was produced in Germany in 1903 [1]. From this year to now, there have been lots of developments in concrete production such as usage of chemical admixtures and new additives like various types of fibers and silica fume, new technologies in manufacturing process.

Concrete could be defined as a heterogeneous material which is composed of aggregates, cement, water and additives. The additives can be chemical admixtures, pozzolanic materials and fibers.

A high amount of natural sources are used in producing concrete. Also huge amount of CO_2 is emitted during production of cement and transportation of raw materials. If less natural sources could be used, concrete production would be a more sustainable process. But is it possible? Developments took place in concrete industry in the last decades showed that some innovative actions may bring more economic and environmentally friendly production options to the sector. This was made possible owing to the vast amount of research carried out in different parts of the world. Efforts to make concrete a more sustainable material are still continuous and for this purpose the main objective of this study was set as; to investigate the effects of magnetically treated water on concrete properties to decrease the amount of raw materials used in production.

Everyone has different expectations from concrete. The producers need to produce concrete with minimum cost by obeying the standard necessities. The workers would like to place and finish concrete easily and the end users need resulting concrete material to be strong and durable against earthquakes and harmful effects. As it is hard to satisfy the needs of producers and consumers at the same time, it is a must that concrete has to be produced, placed and cured with respect to regulations and standards. It has to be known that producing a durable concrete is as important as having high strength concrete. If summarized, concrete can be evaluated in three aspects as given in Figure 1.1.

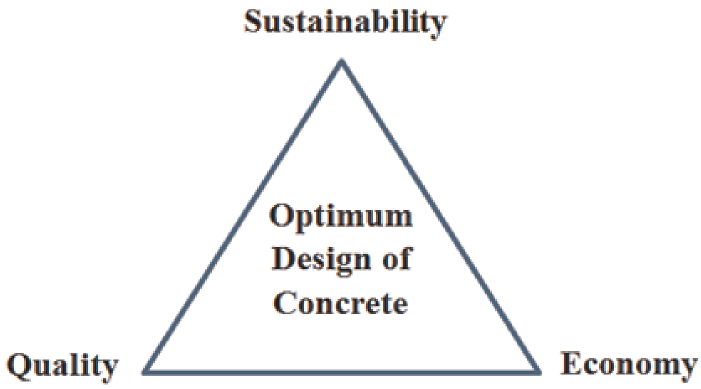

Figure 1.1. Criteria of optimum design of concrete.

Most researchers study concrete in an effort of understanding the impacts and roles of cement, aggregate, admixtures, mineral additives and fibers. However, water which is the least studied constituent has significant effects on properties of fresh and hardened concrete [2]. Water used in concrete production should obey the criteria defined in EN 1008. It must be potable and should not contain harmful materials above the limits defined in the standard. And these are all that most of the civil engineers know only about water used in concrete.

Water has two major roles in concrete which can be summarized as follows: (i) to hydrate the cementitious materials and (ii) to provide workability as a lubricant [3]. In production of concrete, various types of water is used such as tap water, well water, recycled water, pure water etc. The water is stored in closed containers and added to the concrete mixture at the end of the production process. It is the least expensive constituent in concrete. Because of this, both producers and users do not focus on water properties. To understand the structure and micro/macro properties of water, it is needed to look deeply inside water from different aspects. Chemistry and physics tell us that water is not just a substance composed of one oxygen and two hydrogen atoms.

Several researchers investigated the micro and macro properties of magnetically treated water like pH, viscosity, surface tension, dielectric constant and its bonding structure [4, 5, 6, 7]. And some researchers studied the effects of magnetically treated water on concrete properties [8, 9]. After all, researchers from Russia found that the magnetic field can change some properties of water and these changes also affect the properties of concrete such as consistency, compressive strength, tensile strength and degree of hydration etc [10, 11, 12].

In literature, there are few papers and theses about magnetically treated water and its effects on concrete [13, 14]. According to the most researchers, the pH value and viscosity of water is increased and the surface tension is decreased when the water is magnetically treated [5, 6, 7]. However, some researchers think that it is only a hoax. As a result, magnetically treated water and the properties of concrete produced with such water is still a confusing and contradictory subject and more investigations are needed on this subject [15, 16].

In this study, some properties of magnetically treated water and its effects on concrete properties were studied. Based on the previous studies on this subject, it was aimed to find if there can be advantages or not such as:

- Less cement usage in concrete production.
- Less water usage in concrete production.
- Less chemical admixture usage in concrete production.
- Less natural sources usage.
- Less CO_2 emission

2. LITERATURE REVIEW

In this section, a brief summary of the literature about the properties of magnetically treated water and its effects on concrete properties are given.

2.1. Magnetically Treated Water

In literature, different expressions are used to define water that is affected by magnetic fields such as magnetic water, magnetized water, physically treated water, magnetically treated water etc. In this study, “magnetically treated water” and ”treated water” are preferred to express the water treated by magnetization because water can’t be magnetic. Magnetism can only change its some properties.

2.1.1. History of Magnetically Treated Water

In 1920, a German physicist Henrico Anton Lorenz got the Nobel Prize with his study on effect of magnetic field on water [13]. He found that the polar molecules of water are arranged and separated under magnetic field. In 1945, a Belgian engineer first invented a magnetic water treatment machine. This machine contains a powerful magnet inside which creates a magnetic field about 6500 G [14, 17, 18].

In 1962, Russian researchers Alnanina and Wulachoufuski studied the magnetized water effects on concrete [19, 20]. They found that water treated by magnetism can enhance the properties of concrete such as workability and compressive strength. Concrete produced with magnetic water was especially used for military constructions [19]. In 1973, Stuart G. Hibben reported a document about magnetic treatment of water in USA [20]. After this report, researchers from USA were focused on this subject [18]. In 1993, Russian government declared a program called “application of magnetic fields in economy” [15, 21].

In the last five decades, researchers from China, Japan, Egypt, Taiwan, Iraq and

Iran carried out experimental studies to confirm that magnetic water could improve properties of concrete [20]. It must be admitted that this subject is still not very popular in Europe. There are a few studies about the effects of magnetically treated water on medicine side in Europe.

2.1.2. Structure of Water

Before analyzing the properties of water under magnetic field, the micro properties of water should be investigated elaborately, because the changes in macro properties are the results of changes in micro properties.

Water is surely the most important chemical substance for life. According to Thales, it is the material cause of all things [22]. Maybe it is the best explored material, but it has not been understood well, yet [23]. The main reason of this is its unique structural properties [24]. Water is a polar covalent compound and it is composed of two hydrogen atoms joined to one oxygen atom [25]. Polar molecules interact with each other by attraction and this weak attraction is caused by hydrogen bond [26]. The unique properties of water depend on its hydrogen bonding structure and nuclear quantum effects [23]. As shown in Figure 2.1, the water molecule is V-shaped [25].

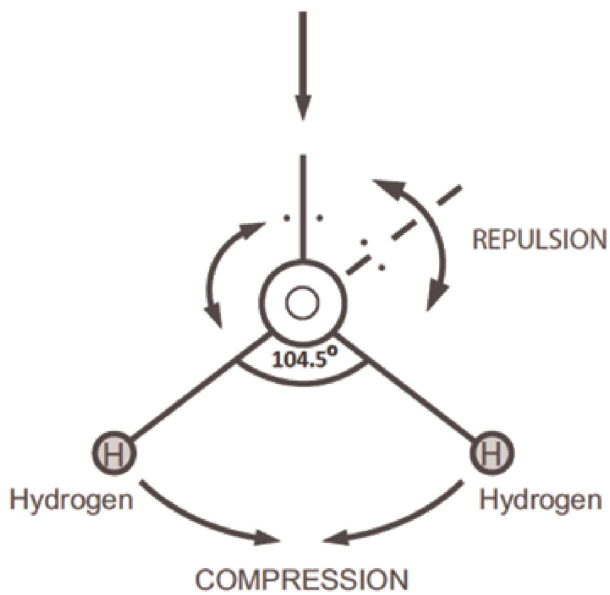

Figure 2.1. Structure of water molecule [2].

Water has a molecular weight of 18.0153 g/mol and has a density of 1kg/l at 4^oC [2]. Oxygen atom has 8 electrons and hydrogen atom has one electron so that one H_2O molecule has 10 electrons. In H_2O molecule, there are two covalent bonds between hydrogen and oxygen atoms and two lone pairs of electrons around the oxygen atom which make bonds with the other water molecules. Because of the repulsion of these lone pairs of electrons, the bonds are oriented to make a stable form [25]. As a result of this, the internal angle is 104.5^o. If there was no repulsion, the angle would have been 109.5^o.

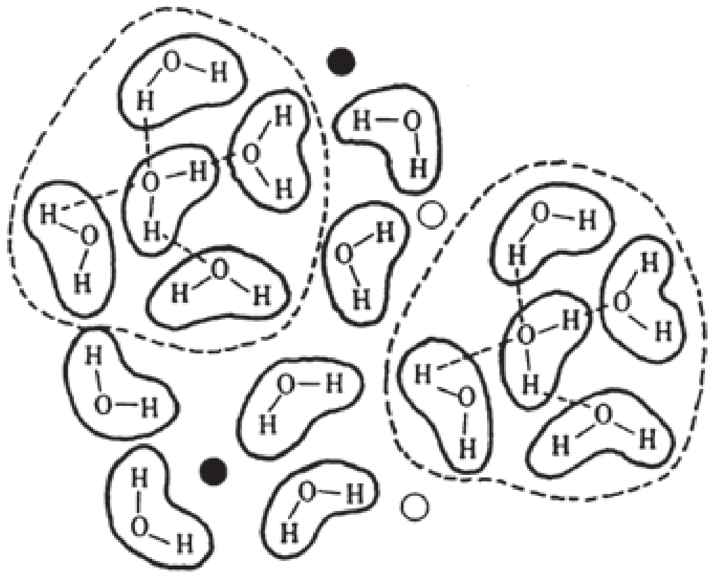

Figure 2.2. Structure of water clusters [27].

Figure 2.2 is an illustration of continuous structure of water molecules. Each water molecule is bonded with four water molecules tetrahedrally by hydrogen bonds [24, 25]. There is an electrostatic attraction between negatively charged oxygen and positively charged hydrogen atoms. The presence of charges on each atoms results in a dipole moment on each water molecules. As a result of this dipole moment, individual molecules bond each other with hydrogen bonds [2, 24]. Hydrogen bonds are formed between the hydrogen atoms and the lone pair of electrons on oxygen as shown in Figure 2.3. Water can only exist as a network of several adjacent water molecules [25]. This form is called water cluster [2].

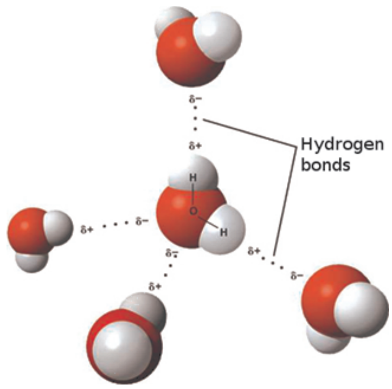

Figure 2.3. Hydrogen bonds between water molecules [2].

The attraction between water molecules creates a strong structure. Without this attraction the boiling point of water would be -80^{o}C [2]. If so, there would have been no life.

Hydrogen bonds between water molecules are very crucial. The changes in these bonds can change the properties of water as seen in Table 2.1 and Figure 2.4.

Table 2.1. Properties of water due to the change on H-bond strength [24].

Property	Change on H-bond Strengthening	Change on H-bond Weakening
Melting point	Increase	Decrease
Boiling point	Increase	Decrease
Adhesion	Increase	Decrease
Cohesion	Increase	Decrease
Compressibility	Increase	Decrease
Density	Decrease	Increase
Dielectric constant	Increase	Decrease
Diffusion constant	Decrease	Increase
Enthalpy of vaporization	Increase	Decrease
Glass transition	Increase	Decrease
Solubility	Increase	Decrease
Specific heat	Increase	Decrease
Surface tension	Increase	Decrease
Thermal conductivity	Decrease	Increase → Decrease
Viscosity	Increase	Decrease

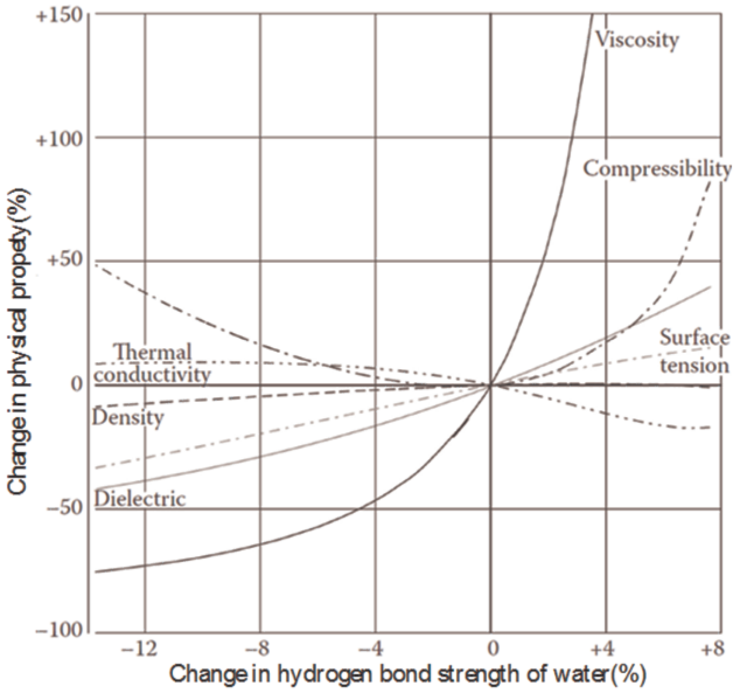

Figure 2.4. Change in physical properties of water due to hydrogen bond strength [24].

2.1.3. Effects of Magnetic Field on Water Properties

When the molecules or elements of a material can be oriented in a stable form by an external magnetic field, the material is called "magnetized" [21]. The most known magnetized materials are iron, nickel and cobalt. All of them are metals. What about water? Can water be magnetized?

For liquids and gases, the ability of being magnetized depends on the number of electrons they have. If the molecule has odd number of electrons, it is "magnetized". Nitrogen dioxide (NO_2) which has 25 electrons is a good example for a compound that can be magnetized. It is one of the most well-known "magnetized" liquid/gas. However, water molecule (H_2O) has 10 electrons. So water is not a "magnetized" material but it is a diamagnetic material [20, 28, 29]. Diamagnetism is the property of an object or a material which causes it to create a magnetic field in opposition to an externally applied magnetic field. As a result, the lone pair of electrons rotates in an opposite direction in each other [25].

According to Yan *et al.*, [25], the orientation of water molecules after magnetization lead to a decrease in amount of hydrogen bonds, cutting of large clusters into smaller ones and reduction in internal angle of covalent bonds . On the contrary, Chang *et al.*, [30] found that under an applied magnetic field the number of hydrogen bonds increase and this causes a more stable and ordered structure. Chang *et al.*, states that, due to the increase in number of hydrogen bonds, the size of water clusters increases and the number of clusters decreases.

Many experiments and studies demonstrate that the properties of water can be changed due to the effect of magnetic field [31]. This is also called "treatment of water by magnetic field". There are also some other water treatment methods such as chemical and physical treatments which can be ionizing radiation process, electrolysis, membrane process, catalytic process, biotechnology and adsorption [32]. Magnetically treated water is generally used in agriculture, medicine, health and some other industries [6, 15, 33, 34]. In the market, there are lots of magnetic devices that treat water magnetically to prevent the scaling of lime in boilers, heat exchangers and domestic hot-water systems [35, 36]. An example of magnetic water treatment device is shown in Figure 2.5.

Figure 2.5. A popular magnetic water treatment device in the market

The main properties of water that can be changed due to an applied magnetic field are [6, 16]:

(i) pH
(ii) Viscosity
(iii) Surface tension
(iv) Electrical conductivity
(v) Optical properties
(vi) Density
(vii) Boiling point

Some physical properties of water and their values under normal conditions (20^{o}C) are given in Table 2.2.

Table 2.2. Properties of water [22].

Property	**Value**
Molecular weight (g/mol)	18
Density (kg/l)	0.998
Heat capacity (cal/g ^{o}C)	1.0
Boiling point (^{o}C)	100
Molecular volume (nm^3)	0.0299
Liquid density maximum (^{o}C)	4
Surface tension (mN/m)	72.8
Viscosity (μPa.s)	1002
Dielectric constant	78.6

It can be said that the properties of water shown in Table 2.2 are unique properties. The heat capacity of water is high compared to other liquids [37]. This means water can store much heat. It behaves like a heat barrier for life. As a result, the temperature change in oceans and seas is very low. The density of water is very important because under +4^{o}C it tends to decrease and so that the density of ice is smaller than liquid water. If it was not, there would have been no life in seas, oceans and rivers, because the water freezes from top surface. The dipole moment of water makes it a good solvent. It is hard to compress water because of its high viscosity [38].

As told before, water molecules form cage-like clusters. So water can be defined as $(H_2O)_n$ instead of H_2O. The tendency of cluster formation of water and the number of water molecules in the clusters can explain the unique properties of water. Generally the number of water molecules in a cluster is between 20 and 200 [39]. The number of H_2O molecules in a cluster is nearly 65 at 0^oC and only 12 at 100^oC, because the number of clusters decreases with an increase in temperature [40]. The number of molecules in a cluster changes rapidly. They form and break up with thermal fluctuations at the micro-scale. A clusters' life time is nearly 10^{-10} seconds [38, 41] and the size of a cluster is about $10^{-3}\mu$m. [41]. Unclustured water is supposed to be "free water" [37].

The water can be diamagnetized after being affected by an external magnetic field and this magnetic field can break down these water clusters and as a result the bond angle can be changed [2].

Toledo *et al.*, [42] measured the binding energy of water and treated water. As shown in Figure 2.6, the apparent magnetic field decreases the cluster stability and weakens the hydrogen bonds of clusters. This study shows that larger clusters are broken to form smaller clusters. The researchers pointed out a statement between intramolecular and intermolecular hydrogen bonds which weakens the stronger intra-cluster hydrogen bonds which are the bonds between O and H atoms (covalent bond) of the same water molecule, breaking the larger clusters and forming smaller ones, with stronger inter-cluster hydrogen bonds which are the bonds between separate water molecules.

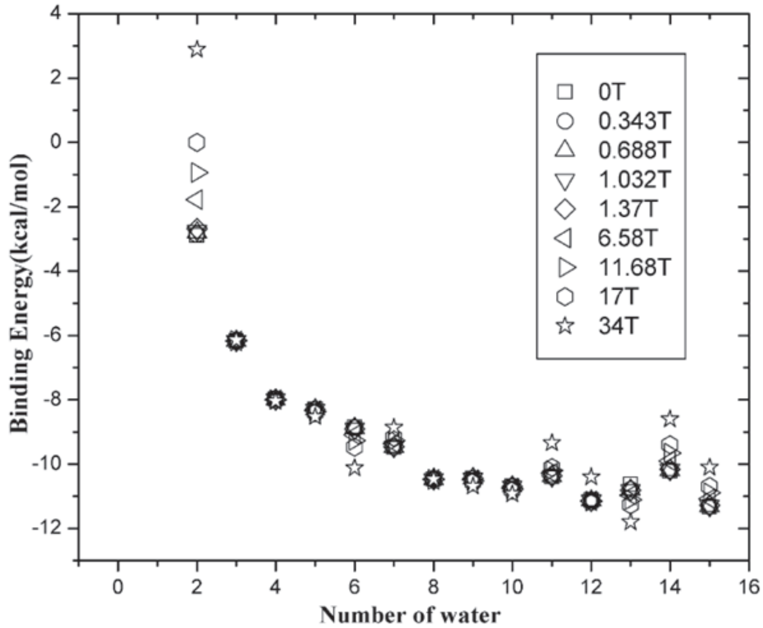

Figure 2.6. Variation of energy with apparent magnetic field.

The hypothesis of the mechanism of water under magnetic field is explained by Lorentz force [43]. When a charged particle moves in a magnetic field, it is pushed by a force perpendicular to its motion as shown in Figure 2.7. This is called Lorentz force (F_L) as shown in Figure 2.1 [44]:

$$F_L = e.vxB \tag{2.1}$$

where [F_L]is the Lorentz force, e is the Charge of the particle(ion), v is the Water flow velocity, B is the Magnetic induction.

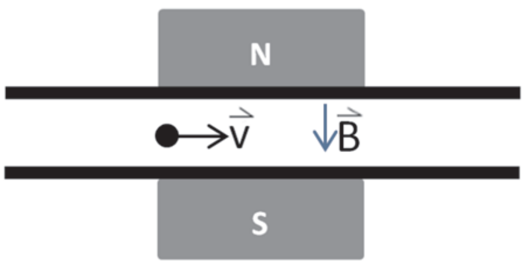

Figure 2.7. Charged ion moving perpendicular to magnetic field [44].

By the effect of Lorentz force the orientation of molecules are changed. The force tends to align the electric dipoles [43]. Because of the diamagnetic property of water, the molecules are oriented opposite to the direction of magnetic field as seen in Figure 2.8 [25].

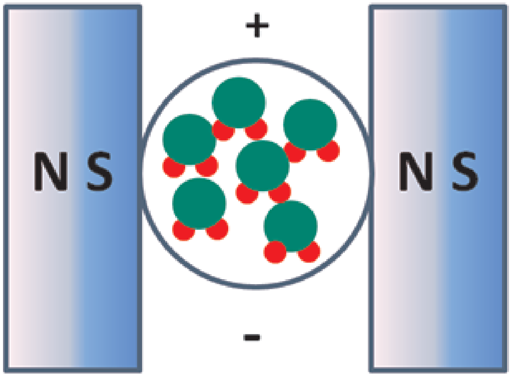

Figure 2.8. Orientation of water molecules under magnetic field [25].

The orientation of molecules makes the clusters broken into smaller parts as seen in Figure 2.9. Smaller clusters with less hydrogen bonds and the decrease in bond angle lead to changes in some properties of water such as density, pH, surface tension, viscosity, permittivity and so on [45].

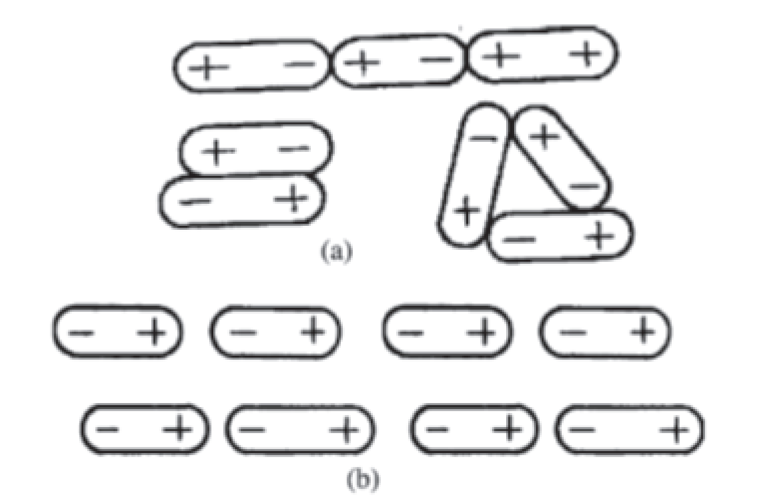

Figure 2.9. (a) Orientation of molecules of stable water clusters, (b) Orientation of molecules after affected by magnetic field [20].

Three main factors that change the properties of water subjected to magnetic field are [13]:

- The magnitude of magnetic field.
- The amount of water subjected to magnetic field.
- The contact time of water with magnetic field.

To create a magnetic field, permanent magnet-based or electromagnet-based devices can be used. Permanent magnets are made from iron-based, nickel-based, cobalt-based or other earth element-based compounds. Most of them generate a magnetic field less than 1 T [32]. To generate a higher magnetic field that is effective for short distances, neodymium magnets can be used which are permanent magnets made up of an alloy of neodymium, iron, and boron to form $Nd_2Fe_{14}B$. Neodymium magnets, as seen in Figure 2.10, are coated to be prevented from corrosion. The main advantages of this type of magnet are its high energy production, very high coercive force and moderate temperature stability [46]. Electromagnets produce magnetic field by a flow of electric current. An electric current passing through a wire which is wound on a coil with many turns creates a magnetic field around the wire [21].

Figure 2.10. Neodymium magnets.

There are different types of magnetic fields obtained by neodymium magnets as seen in Figure 2.11. The best results are expected when the water flows through the magnetic field and the magnetic field should be perpendicular to the direction of flow.

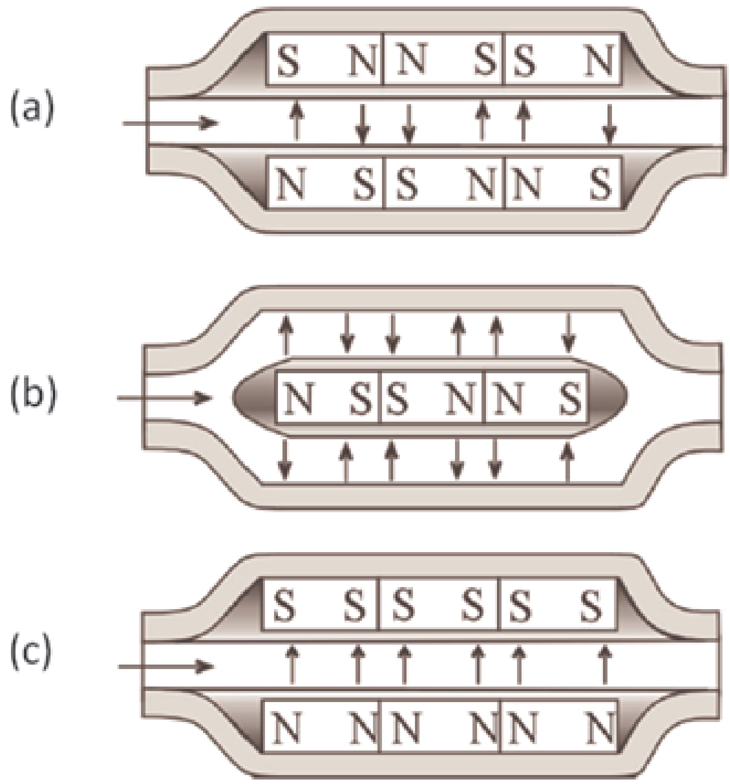

Figure 2.11. Some types of magnetic field [47].

2.1.3.1. *pH* Value. The pH value is the measurement of solvated hydrogen ions in a solution [48]. To evaluate the pH value of a liquid the concentration of hydrogen ions is measured. As known, pH value greater than 7 refers to a basic (alkaline) solution and smaller than 7 refers to an acidic solution. Pure water at 25^{o}C has a pH value of 7. It is neuter. The organic compounds, solutes, contaminants and other impurities in water can change the pH value. The pH value can be measured by both pH meters and indicators.

AbdelTawab *et al.*, [49] tried different types of magnetic treatment devices to measure the pH change of drainage, well, tap and sea water. All treatment devices were made up of a pipe surrounded by magnets. The water was circulated in a closed system composed of pipe, treatment device, a pump and a tank. They measured the pH value of water at every 20 minutes for 2 hours. As a result they found that the pH value of water is increased when it is treated by magnetic field and as treatment time increases the pH value increases much. The measured pH values of different types of water are listed in Table 2.3.

Table 2.3. The pH value of water due to water type, conditioner type and period [49].

Water Type Conditioner Type				
	Drainage water MAG3	Well water MAG-SOL200	Tap water H_2FLOW	Sea water A100s
Time	*pH*			
0	7.42	8.04	7.73	7.56
+20 min	7.56	8.18	7.74	7.87
+40 min	8.07	8.2	8.26	7.94
+60 min	8.08	8.23	8.31	7.98
+80 min	8.37	8.42	8.34	7.98
+100 min	8.4	8.47	8.37	7.98
+120 min	8.42	8.52	8.4	7.98

Wang *et al.*, [45] studied the impermeability mechanism of concrete produced with magnetically treated water. They measured the changes in pH of water under different flow rates and magnetic field intensity. They found that the increase in intensity of magnetic field and the decrease in flow rate can result in an increase in pH value as shown in Table 2.4.

Table 2.4. The pH value of water due to magnetic field intensity and flow rate [45].

Magnetic field intensity (mT)	0	230 mT	280 mT	330 mT	230 mT	280 mT	330 mT
Water flow rate (m/s)	0	2.0 m/s	2.0 m/s	2.0 m/s	1.0 m/s	1.0 m/s	1.0 m/s
pH value	7.52	7.52	7.53	7.54	7.52	7.55	7.61

Gonet [7] studied the effect of constant magnetic field on certain properties of water. He produced magnetically treated water by an electromagnet with a pole diameter of 200 mm. He used triple-distilled water and tap water as control and treated water as exposed. He set the flow rate as 1 cm/sec and the intensity of magnetization as 0.8 T. According to his study, he found very small changes in pH value that were not greater than the standard deviation of the test. He considered that magnetic field does not change the pH value of distilled and tap water.

Kirgintsev *et al.*, [50] studied the mechanism of the process of magnetically treated water in 1963. They used electromagnetic apparatus to produce treated water. They treated distilled water with an initial pH of 4.2 at various magnetic field intensities. They found pH of water as 5.18 in 420 Oersteds field, 5.47 in 520 Oersteds field and 5.00 in 650 Oersteds field.

Quickenden *et al.*, [51] studied the effect of magnetic fields on the pH of water. Firstly, they recorded the pH of flowing normal water for 10 minutes and then they placed a 4700 G magnet on the siphon. This time they recorded the pH of flowing treated water for 20 minutes. Finally, they removed the magnet and recorded the pH for 10 minutes. All the measurements at constant flow rate did not fluctuate by much than ± 0.04 pH. They did the same experiment with different flow rates but in any case they did not find a worth able change in pH value. They also did the same experiment with an electromagnet which had various intensities from 0 to 24 T. This time pH changed as 0.1 unit.

<u>2.1.3.2. Surface Tension.</u> Surface tension is a contractive tendency of the surface of a liquid that allows it to resist an external force [48]. It can be also said that it is the surface energy per unit area [52]. Because of the internal attraction of water molecules, the surface of water acts like a skin under tension. As the temperature increases, the surface tension of water decreases [2].

Amiri *et al.*, [4] studied the magnetic effect on the surface tension of pure and tap water. Because of low reproducibility, they only published the data of pure water. In their study, they did over than 200 tests in different conditions during a period of six month. They used a commercial magnetic conditioner which was consisted of 4 ceramic permanent magnets with a minimum strength of 3850 G. The conditioner was located on a plastic pipe with a diameter of 0.75 inches. To measure the surface tension of water, a German made Processor Tensiometer K-12 was used. All measurements were carried out at a temperature of 20±1°C. They investigated the change in surface tension of pure water due to frequency (passing number of water) and time. It was found that surface tension of water is changed due to magnetic effect and the surface tension of water is decreased as frequency increases. But it turns into stable after a certain frequency level. As seen in Figure 2.11, the surface tension of pure water is nearly 71 mN/m and after one time passing of pure water in magnetic field, the surface tension decreases to 63 mN/m. They also found that the surface tension of magnetically treated water is increased by time.

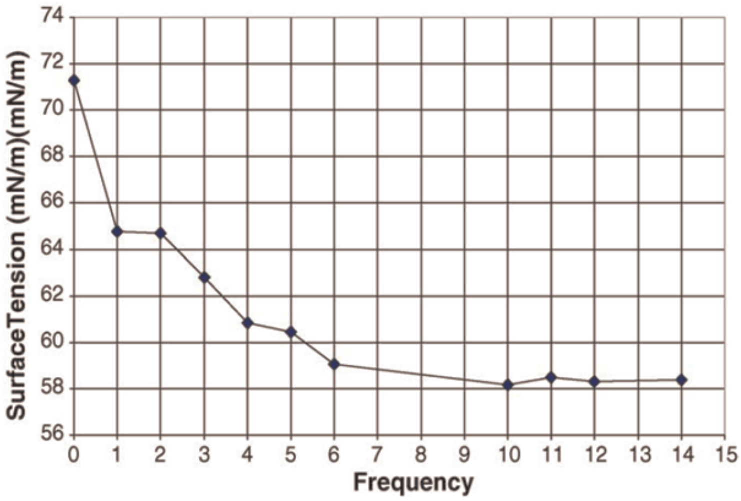

Figure 2.12. Surface tension of water due to passing frequency [4].

Yang *et al.*, [5] measured the surface tension of water by using the plate method. Krüss-K12 tension meter, which had a 0.01mN/m precision, was used for the test. The measurements were taken at 20°C and at an RH level of 40-50%. They found that magnetic treatment causes a decrease in surface tension of water. They also measured the relative variation of molecular energy of water. It was found that after magnetization the molecular energy decreases like surface tension as shown in Figure 2.13.

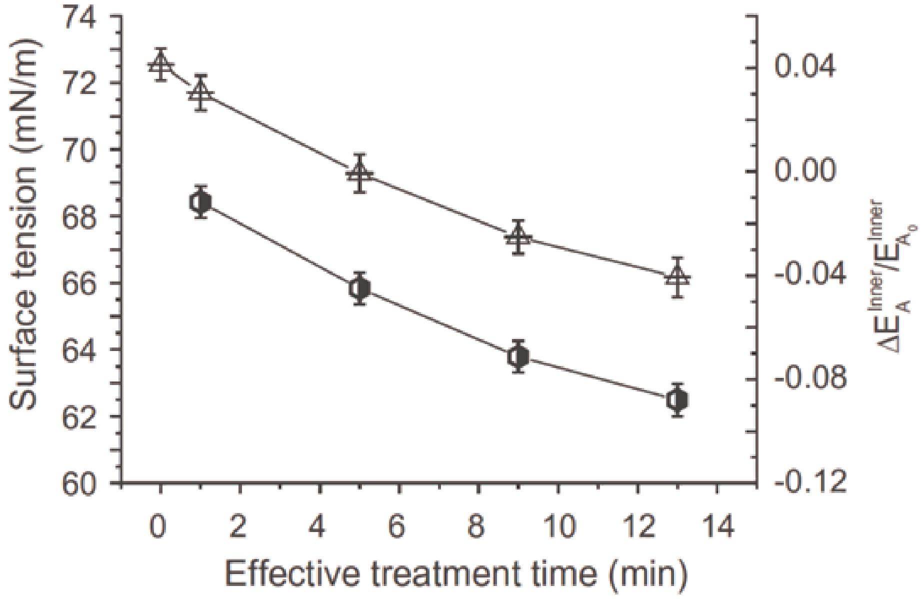

Figure 2.13. Surface tension of water due to magnetization period [5].

The effect of flow rate and magnetic field intensity on surface tension was studied by Wang *et al.*, [45]. According to their study, the surface tension of water decreases under magnetic field and the lower the flow rate is, the lower the surface tension is.

Pang *et al.*, [6] investigated the changes in properties of water under the action of magnetic field. One of the subjects they investigated was about the changes of surface tension force of magnetically treated water. To measure the surface tension, they used OCA40 Micro Optical-Vision instrument with an accuracy of $\pm 0.3^o$. The measurement method is surface tension plate method. They used three different plates which were muscotive, copper and graphite. Muscotive is hydrophilic but copper and graphite are hydrophobic materials. The water was exposed in a magnetic field of 4400 g for 30 minutes. It was found that there is no difference for the contact angles of pure water and treated water on muscotive. For copper, the contact angle of treated water is 146.8^o and pure water is 147.2^o. On the other hand for graphite, the contact angle of treated water is 91.2^o and pure water is 91.6^o. As a result, it is shown that the surface tension of treated water is lower compared to pure water. According to the authors, the decrease of contact angles of magnetically treated water was due to the change in clustering structure of water molecules.

Gonet [7] studied the effect of constant magnetic field on surface tension of water. The measurements were carried out by using a stalagmometer. The test accuracy was 0.2%. He notified that the method was not very exact to measure the surface tension. Two field strengths of 0.12 T and 0.80 T were applied. As a result, he found exactly no significant change in surface tension between control and exposed water.

Song *et al.*, [9] tested surface tension of concrete admixtures on KRUSS -K12 machine. The result of this study is important because it is the only study that can be found in literature about the effects of magnetic treatment of concrete admixture. The test was conducted at 20±1^{o}C. After an investigation they found that the optimum magnetic field strength was 810 mT and the flow velocity was 0.73 m/s. They created the magnetic field by using 0.667 T NdFeB magnets. They used two types of admixture that were named as CF(inorganic based) and SW-4(organic based). The admixture dosages were 0.5% and 1.5%. They decided that the surface tension is reduced when the admixtures were exposed to a magnetic field. The surface tension values they measured are given in Table 2.5.

Table 2.5. The change of surface tension of admixtures due to magnetic treatment [9].

Specimen	**Admixture dosage (%)**	**Surface Tension (mN/m)**
Unmagnetized CF	0.5	47.26
Magnetized CF	0.5	44.33
Unmagnetized SW-4	1.5	68.38
Magnetized SW-4	1.5	65.89

Cho *et al.*, [52] investigated the surface tension of tap water, hard water and treated water. They used permanent magnets and electromagnet device for treating the water. The treatment system consisted of a pump, magnetic field generator, flow meter, reservoir, valve and pipe. The magnetic intensity of magnets was 0.16 T. The flow velocities were 6.3 m/s for the system with permanent magnets and 1.0 m/s for the system with electromagnet. They circulated the water through solenoid-coil 1, 2, 5, 10 or 30 times to measure the surface tension. For the tap water, the maximum decrease in the surface tension was 7.7% and for the hard water, it was 8.2%. The maximum decrease was seen when the passing number of water through the system was 30.

Huo *et al.*, [53] carried out a study about the effects of magnetization on surface tension water. They treated water by electromagnets and measured its surface tension by drop shape method. The intensity of magnetic field was between 0 and 0.86T. The flow velocity was between 0.169 s/m and 0.369 s/m. They found that there is an increase in surface tension of water when it is magnetically treated. They concluded that the best magnetic field intensity for magnetizing water is 0.2-0.3 T and they decided that the intensity of magnetization should not be too high to reduce the surface tension of water.

2.1.3.3. Viscosity. Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress. In other words it is the resistance of fluid to flow [42]. Newtonian materials such as water have constant viscosity. The rise of temperature decreases the viscosity of water [54]. Studies have found that magnetic field also influences the viscosity of water [42].

Pang *et al.*, [31] measured the viscosity of water at two different magnetic fields of 3000G and 4000 G. They found that the viscosity of water decreases under the effect of magnetic field. They also found that the higher the magnitude of magnetic field the lower the viscosity.

Yang *et al.*, [5] carried out measurements of viscosity of water affected my magnetic field. They used a modular compact rheometer for viscosity measurements. The measurements were performed at room temperature. They found that the longer the magnetic treatment time is, the more viscous water is as seen in Figure 2.14. According to their experiment they drew a conclusion that during the magnetic treatment new hydrogen bonds were formed.

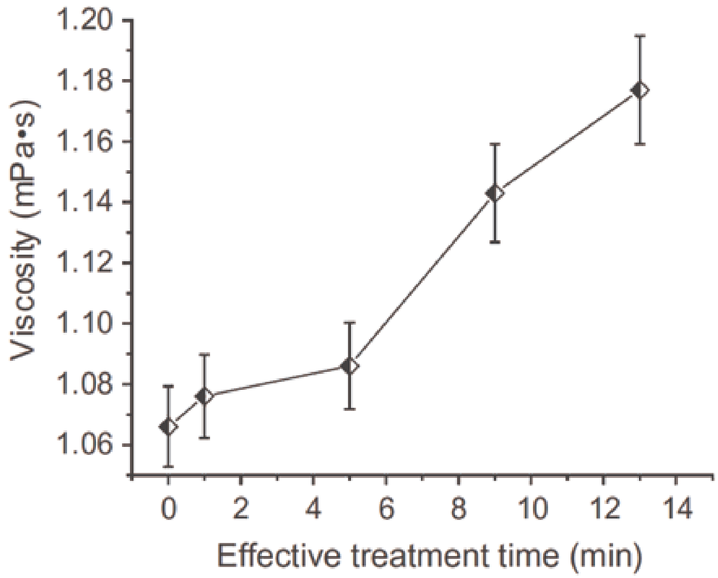

Figure 2.14. Viscosity of water due to magnetization time [5].

Ghauri *et al.*, [55] investigated the change of water viscosity under the influence of magnetic field. An Ubblehode viscometer was used for the test. The permanent magnet had strength of 7.5kG. The accuracy of the flow time measurement in viscometer was $\pm$ 0.02s. At 25^{o}C the viscosity of distilled water was found as 0.8904 mPa.s and of treated water was found as 0.8915 mPa.s.

Song *et al.*, [46] measured the viscosity of water using a German made Physica MCR 300 viscometer. They treated the water with a 0.5 T permanent magnet and the flow rate of water was 1 m/s. They found that the viscosity of water increases with increasing treatment time as shown in Figure 2.15.

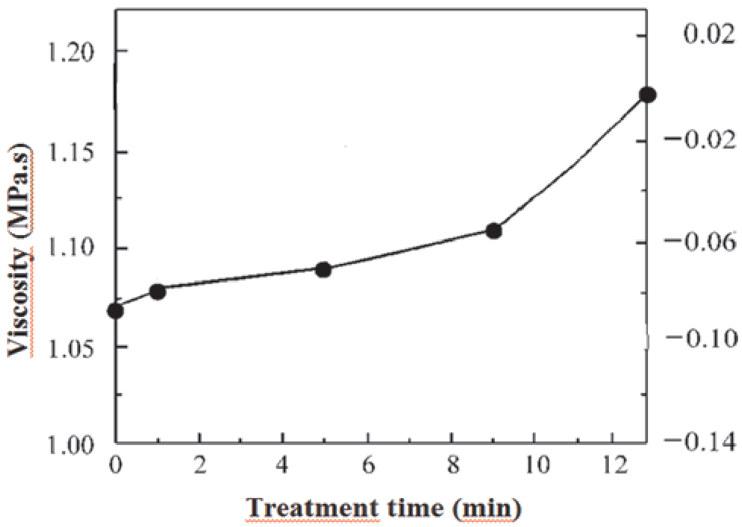

Figure 2.15. Viscosity of water due to magnetic treatment time [46].

Toledo *et al.*, [42] measured the viscosity of water and magnetically treated water and they found that magnetization increase the viscosity of water. The viscosity of water and treated water they measured were 964.42μPa.s and 996.63μPa.s, respectively.

2.1.3.4. H-NMR Analysis. Nuclear magnetic resonance(NMR) spectroscopy is a technique used to determine a compound's unique structure. The atomic nucleus is a spinning charged particle, and it creates a magnetic field. The nuclear spins are random and spin in random directions without an influence of an external magnetic field. If there is an external magnetic field, the nuclei align themselves either with or against the field [56]. The characteristic life-time of a spin in the upper state is called the spin-lattice relaxation time (T1). T1 is the average length of time that a proton remains in the same energy level. The spin-lattice relaxation time is also called the longitudinal relaxation time.

When T1 increases, the half-height width of the frequency peak decreases as shown in Figure 2.16. The narrowing of the width means that the water clusters' size gets smaller. In Figure 2.17, the effect of T1 relaxation time on molecular size is shown.

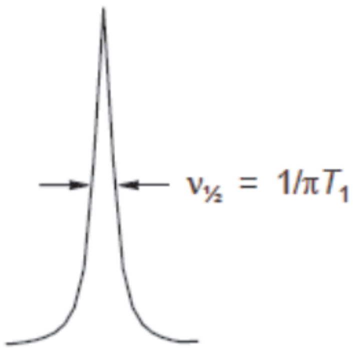

Figure 2.16. Half-height width of the frequency peak.

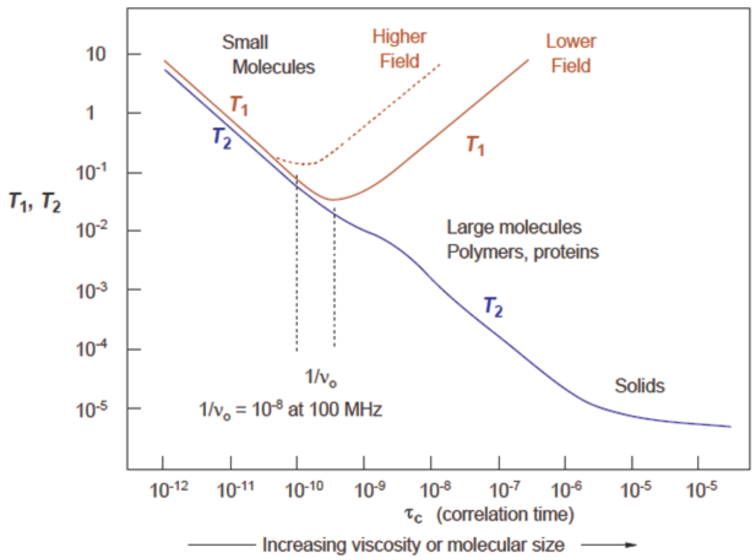

Figure 2.17. Relaxation time versus correlation time.

T1 may change if the sample is put in a magnet with a different field strength (Bo) as seen in Formula 2.2. A larger Bo will lead to a longer T1 [57].

$$\vartheta_o = \gamma B_o/2\pi$$
$$\frac{1}{T_1}\alpha\frac{1}{\vartheta_o} \tag{2.2}$$

ϑ_o= Frequency γ= Gyromagnetic ratio B_o= Magnetic field strength

Yang *et al.*, [5] measured NMR relaxation of water on a Bruker Avance DRX-400 spectrometer which has a proton frequency of 400 MHz. The test was performed at

20^oC. The sample water and deuteroxide were put inside a tube with a diameter of 5mm. They found that the rotational motions of water molecules get slowdown from the proton NMR spectrum. Due to this situation, they claimed that after magnetization more hydrogen bonds are formed and water clusters size get larger.

According to a NMR test conducted at NuMega Resonance Laboratory [26]; it was found that there is an increase in proton peak width and proton dispersion when the water is treated by magnetic field. As shown in Figure 2.18 the width of the proton pick in regular water is 0.1 ppm and 0.25 ppm in treated water.

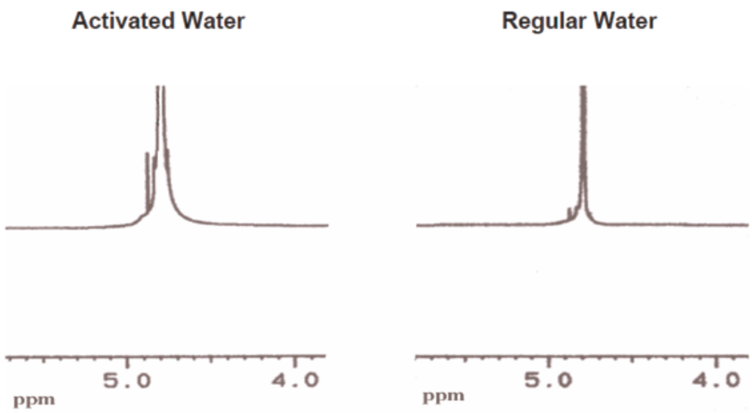

Figure 2.18. The width of proton pick of activated and regular water [26].

Badawi *et al.*, [58] measured T1 time of water and treated water. They found that T1 time increases when the water is magnetically treated as shown in Table 2.6.

Table 2.6. T1 time of tap and treated water [58].

Sample	**T1(sec)**
Tap water	0.67
Treated water	1.51

2.1.3.5. Oxygen NMR(O-NMR) Analysis. The density and clustering of water molecules can be determined by O-NMR. O-NMR analysis gives a spectrum of the material. The half-height width of the peak on the spectrum indicates the size of the molecule or water cluster as determined by its rate of rotation or relaxation time. Smaller the half-height width is, less molecules per cluster contains. The width of the frequency of half peak height of O-NMR spectrum shows the relative average size of clusters in water. The wider spectrum shows that the clusters are bigger and the narrower spectrum shows that the clusters are smaller [59, 60].

Shin [61] conducted O-NMR analysis for several type of water samples and he found that line width of magnetically treated water is narrower than tap water as seen in Table 2.7.

Table 2.7. Half-height width of treated, tap and drinking water.

Sample	**Line width (Hz)**
Magnetically treated water	67
Home tap water	84
Home drinking water	109

According to a study of Tsinghua University in Peking [59], the half peak width of clustered water is narrower as shown in Table 2.8. The frequency of clustered water which has smaller size clusters is 67 Hz. This value is smaller than the other water samples.

Table 2.8. Half-height width of clustered, glacier and rain water.

Sample	**Line width (Hz)**
Clustered water	67
Glacier water	69
Rain water	106

2.1.3.6. FTIR Analysis. FTIR (Fourier Transform Infrared) analysis provides spectral information which is a molecular fingerprint for organic, polymeric, and inorganic materials. This technique is very useful for identifying base polymer compositions and organic contaminants. Unknown materials can be compared by FTIR for "best matches" with libraries of spectra which have been cataloged for known materials. By FTIR analysis unknown materials and the amount of components in a mixture can be identified. Each compound corresponds to a frequency level and this frequency is unique for all materials [62].

2.2. Effects of Magnetically Treated Water on Concrete Properties

There are some theories about the effects of magnetically treated water on concrete properties but the studies about this subject are still contradictory. Probably the main reasons of this situation result from different laboratory conditions, low reproducibility and the efficiency of magnetic field etc. [42].

As told before, water molecules are in the form of clusters and the number of water molecules in a cluster depends on temperature, pressure and impurity of water. After applying a magnetic field to water, the size of the clusters and the surface tension of water decrease [19, 20]. As a result, the water is much effective for hydration reaction. Because small water clusters can hydrate cement better. As known cement hydration starts up from the surface of cement grain [2] and by the time a dense layer composed of hydration products covers the cement grain surface. This dense layer can make water hard to diffuse into the unhydrated cement zone. But small water clusters can diffuse easier [20].

Afshin *et al.*, [19] explained that because of the smaller clusters caused by magnetization, the thickness of the water layer on the cement grain is thinner than normal water. This causes a reduction in water demand for hydration and thus w/c ratio decreases.

2.2.1. Compressive Strength

Song *et al.*, [9] studied the effects of admixtures treated by magnetic field on concrete compressive strength. The magnetic field strength was 810 mT and the flow velocity was 0.73 m/s. They used two types of admixture that were named as CF (inorganic based) and SW-4(organic based). The admixture dosages were 0.5% and 1.5%. As a result, they found that using magnetically treated admixture resulted in an increase in compressive strength at 3^{rd}, 7^{th} and 28^{th} day. They found that there can be a 20% increase in compressive strength at 28th day when the admixture is treated.

Afshin *et al.*, [19] used a German made magnetic treatment device to produce magnetic water for concrete production. They circulated water for 15 minutes with a flow rate of 0.04 l/s and used this water in concrete production. According to their study the test variables were water/cement ratio, cement content, superplasticizer content and water type. They found that the compressive strength of concrete increases when magnetic water was used. They prepared 21 different mixtures. They found the highest increase in the compressive strength of concrete when they used 450 kg/m^3 of cement, 180kg/m^3 of water and 2% amount of superplasticizer. The increase in compressive strength was 34.2%. They also reported that there can be a saving of cement when magnetic water is used.

Ahmed [21] investigated the effects of different magnetic field intensities, treatment time and flow velocity on properties of concrete. He observed the best results when the strength of magnetic flux was 1.2 T, the flow velocity was 0.71 m/s and the treatment time was 4.5s/l. He produced treated water with an electromagnetic field generator. He found that the strength of concrete prepared with magnetized water increases up to 10-20% as shown in Table 2.9.

Table 2.9. Compressive strength of concrete [21].

Specimens	Treatment time (l/s)	Velocity of flow (m/s)	7-day average compressive strength (MPa)
N (normal water)	-	-	27.10
M1	2.5	1.27	32.50
M2	4.5	0.71	32.80
M3	7.5	0.42	32.50
M4	10.0	0.32	31.00
M5	12.5	0.25	30.25
M6	15.0	0.20	30.00

Arabshahi [17] prepared 52 concrete samples which were produced by ordinary water and 52 samples which were produced by magnetic water. He categorized them as A (non-magnetic) and B (magnetic). The average compressive strength of group A at 28 days was 265 kgf/cm^2 and group B was 325 kgf/cm^2. The increase was nearly 22%.

Nikoo [13] studied the effects of the velocity and frequency of passing water through a magnetic field on mechanical properties of concrete. He found that the compressive strength could be increased by 27% when magnetic water was used.

Abdel-Raouf *et al.*, [15] studied the compressive strength of concrete produced with magnetic water and tap water. They produced concrete mixtures with different cement content, w/c ratio and concrete admixtures. They exposed tap water to different magnetic field intensity. According to their study, magnetization of water did not affect the 28-day compressive strength of concrete. But a slight strength reduction was seen at 3-day strength.

Su *et al.*, [20] used a magnetic-field generating machine which can produce a magnetic field up to 5 T. They treated the tap water with different intensities. They produced a concrete with various amount of fly ash with a w/b ratio of 0.485. They measured the compressive strength of concrete mixtures at 7, 28, 56 and 90 days. They found the maximum increase in compressive strength when the tap water was treated under 0.8 T. The increase at different ages was between 5% and 10%.

Su *et al.*, [10] also studied the effect of magnetic water on the engineering properties of concrete including ground granulated blast furnace slag (ggbfs). As seen in Table 2.10, there is an increase in compressive strength when magnetic water is used and the best results were obtained when the magnetic field was 0.8 T and 1.2 T

Table 2.10. Effect of water that is treated under various magnetic fields on concrete strength [10].

	Effect of magnetic water on compressive strength of concrete samples (MPa)						
Age(days)	0 T	0.2 T	0.4 T	0.6 T	0.8 T	1.2 T	1.35 T
7	27.1	30.1	29.8	29.6	32.5	29.0	28.0
28	29.6	34.5	33.2	34.2	36.9	32.9	31.4
56	33.7	38.0	36.9	37.0	40.0	37.6	35.5

Ebrahimi *et al.*, [63] demonstrated the effect of magnetic water on strength and consistency of self-compacting concrete. The results of their study are shown in Table 2.11. The increase in compressive strength is between 20% and 35%.

Table 2.11. Compressive strength of concrete [63].

Number	Cement content (kg)	W/C	Superplasticizer ratio (%)	28 day compressive strength with normal water (kgf/cm^2)	28 day compressive strength with magnetic water (kgf/cm^2)	Increase in strength (%)
1	480	0.4	1	425	572	35
2	480	0.45	1.5	401	498	24
3	500	0.35	1.5	363	487	34
4	500	0.38	1.5	499	598	20
5	540	0.38	1	440	581	32
6	600	0.35	1.5	409	554	35
7	600	0.38	1	436	540	24
8	600	0.5	1	348	445	28
9	600	0.5	1.5	309	400	29

Wang *et al.*, [64] used magnetically treated water in production of sprayed concrete. They produced 3 sets of concrete which of two were produced with different types of rapid setting admixture. One of them was produced without admixture. They used permanent magnets to treat the water. They also tried to investigate the effect of magnetic pole orientation. They found an increase in early strength of concrete when the water was treated by magnets as seen in Table 2.12.

Table 2.12. Compressive strength of concrete [64].

Set number	Water type	Magnetic Pole	Admixture type	1-day strength (MPa)	7-day strength (MPa)
1	Normal	-	-	6.22	18.56
	Magnetically treated	Opposite	-	8.21	19.34
	Magnetically treated	Same	-	8.10	18.75
2	Normal	-	1	7.42	17.26
	Magnetically treated	Opposite	1	8.98	17.78
	Magnetically treated	Same	1	8.20	18.16
3	Normal	-	2	7.17	15.35
	Magnetically treated	Opposite	2	8.60	16.02
	Magnetically treated	Same	2	8.53	17.02

Pang *et al.*, [8] studied on effects of magnetically treated water on concrete properties. They used purified water at 25^{o}C that is exposed to magnetic field of 4400 G. They found that the compressive strength of concrete can increase up to 10%.

2.2.2. Workability

Many researchers have been studying the magnetic water effects on concrete consistency. Most studies proved that there is an improvement in consistency. As it is known concrete is a rigid-gel material and it loses its workability by time. At construction site, the concrete should have enough workability to be placed, pumped and finished.

Song *et al.*, [9] studied the effects of admixtures treated by magnetic field on workability of concrete. As told before, they used two types of admixture that were named as CF (inorganic based) and SW-4 (organic based). The admixture dosages were 0.5% and 1.5%. They found that the slump was increased when magnetically treated CF type of admixture was used. On the other hand, the slump was decreased when SW-4 type of admixture was used. It can be concluded that the type of admixture can affect the efficiency of magnetization. They did not report any reasons for this situation.

Afshin *et al.*, [19] performed slump tests for concrete produced with non-magnetic water and magnetic water. Their study demonstrated that there can be an increase in slump value up to 45%. They explained this situation by the change in size of water clusters and reported that when the clusters' size got smaller, the water demand for hydration reaction decreased.

Most of the researchers produced concrete with very low slump values. In fact, in construction sector in Turkiye, the most demanded slump value is 17-20 cm. Ahmed [21] produced concrete below a slump value of 7 cm. He found that there is an improvement in workability of concrete when magnetically treated water is used as shown in Table 2.13.

Table 2.13. Slump of concrete [21].

Specimen	**Treatment time (l/s)**	**Velocity of flow (m/s)**	**Slump (mm)**
N (normal water)	-	-	20
M1	2.5	1.27	55
M2	4.5	0.71	65
M3	7.5	0.42	50
M4	10.0	0.32	45
M5	12.5	0.25	40
M6	15.0	0.20	40

Arabshahi [17] studied the effect of magnetic water on concrete workability. The variables of his study were magnetic field intensity, treatment time, cement content and water/cement ratio. His study showed that there is an improvement in slump of concrete. The average slump value of concrete samples produced with ordinary water was 4 cm. Whereas, the average slump value of concrete produced with magnetic water was 11 cm.

Abdel-Raouf *et al.*, [15] showed that there is an enhancement in concrete slump with enough slump retention as shown in Table 2.14. They evaluated the values within each set. In set three, the minimum increase in slump was nearly 50% and the maximum increase was almost 300%. They also studied whether there is slump retention or not when magnetically treated water is used in concrete production. After measuring the slump of concrete mixtures of set 1, the mixtures were monitored for 90 minutes at a temperature of 22^{o}C - 25^{o}C. And then the slump was again measured in every 15 minutes. It was found that there is an improvement in slump retention Table 2.15.

Table 2.14. Slump of concrete [15].

Set Number	**Magnetic field intensity (T)**	**W/C ratio**	**Admixture type**	**Slump (mm)**
1	-	0.45	-	5
1	0.1	0.45	-	20
1	0.2	0.45	-	70
1	0.3	0.45	-	120
1	0.4	0.45	-	75
2	-	0.45	Type A	150
2	0.1	0.45	Type A	180
2	0.2	0.45	Type A	150
2	0.3	0.45	Type A	170
2	0.4	0.45	Type A	160
3	-	0.35	Type F	65
3	0.1	0.35	Type F	95
3	0.2	0.35	Type F	120
3	0.3	0.35	Type F	150
3	0.4	0.35	Type F	210

Table 2.15. Slump retention of concrete [15].

Magnetic field intensity (T)	Slump at 0 min (mm)	Slump at 15 min (mm)	Slump at 30 min (mm)	Slump at 45 min (mm)	Slump at 60 min (mm)
-	5	0	0	0	0
0.1	20	10	3	0	0
0.2	70	60	45	25	10
0.3	120	80	40	35	25
0.4	75	60	45	25	10

According to the study of Ebrahimi *et al.*, [63] the flow value of self-compacting concrete increases when the concrete is produced with magnetic water as seen in Table 2.16.

Table 2.16. Flow value of self-compacting concrete [63].

Number	Cement content (kg)	W/C	Superplasticizer ratio (%)	Flow with normal water (mm)	Flow with magnetic water (mm)	Increase in flow (%)
1	480	0.4	1	550	632	15
2	480	0.45	1.5	570	680	19
3	500	0.35	1.5	610	732	20
4	500	0.38	1.5	570	673	18
5	540	0.38	1	600	702	17
6	600	0.35	1.5	620	719	16
7	600	0.38	1	590	714	21
8	600	0.5	1	605	720	19
9	600	0.5	1.5	620	725	17

2.2.3. Durability

Permeability of concrete is an important criterion for durability of concrete. Less permeable concrete is much durable. The permeability of concrete can be determined by rapid chloride ion permeability test and water penetration under pressure test.

2.2.3.1. Rapid Chloride Permeability Test. Abdel-Raouf *et al.*, [15] examined the rapid chloride ion permeability of concretes produced with tap water and magnetically treated water. They produced 3 different concrete mixtures with different admixture types and w/c ratio. It was found that magnetic treatment does not lead to a significant change in resistance to chloride ions penetration. The relative coefficients of permeability of concrete mixtures are shown in Table 2.17. in

Table 2.17. Rapid chloride permeability test results.

Set Number	Magnetic field intensity (T)	W/C ratio	Admixture type	Charges measured (coulomb)	Relative coefficient of permeability (10^{-7} m/s)
1	-	0.45	-	932	8.8
1	0.1	0.45	-	1092	1.6
1	0.2	0.45	-	985	8.2
1	0.3	0.45	-	734	1.3
1	0.4	0.45	-	772	1.6
2	-	0.45	Type A	653	3.9
2	0.1	0.45	Type A	869	4.6
2	0.2	0.45	Type A	745	1.5
2	0.3	0.45	Type A	699	2.1
2	0.4	0.45	Type A	935	1.2
3	-	0.35	Type F	326	5.2
3	0.1	0.35	Type F	494	7.2
3	0.2	0.35	Type F	432	9.8
3	0.3	0.35	Type F	533	1.6
3	0.4	0.35	Type F	426	4.9

2.2.3.2. Water Permeability Test. Abdel-Raouf *et al.*, [7] performed water permeability test by applying a water pressure of 30 bars for 24 hours to concrete cylinders. They explained that magnetic treatment on water does not cause a reduction in permeability of concrete. Permeability of concrete mixtures are shown in Table 2.17.

Some studies in literature were summarized in this section. Although there are a few studies about this subject in literature, enough amounts of academic documents could be found by a comprehensive search. And it was decided to investigate not only in concrete side but also in water side because of the contradictory information. Many papers and studies about the effects of magnetically treated water on concrete properties do not contain information about the water. So it is hard to understand the effect on concrete. In this study, properties of magnetically treated water were investigated and by the way there could be a literature correction. And it was aimed to understand the effects on concrete due to the changes in water properties.

3. EXPERIMENTAL STUDY

3.1. Materials

In this section, the properties of concrete components were given. The analysis reports of the materials were obtained from the producers. All the properties of materials were checked if they were suitable or not according to related standards.

3.1.1. Cement

The cement used for producing concrete mixtures was CEM I 42.5 R which was obtained from Akçansa Büyükçekmece Cement Plant. The physical, mechanical and chemical properties of the cement are given in Table 3.1, Table 3.2 and Table 3.3, respectively.

Table 3.1. Chemical properties of cement.

CHEMICAL REQUIREMENTS TEST METHOD : TS EN 196-2	Standard Limits	Test Results (%)
SiO_2 (soluble)		21.13
Insoluble Residue	$\leq$ 5.0	0.41
Al_2O_3		4.98
Fe_2O_3		3.73
CaO		65.23
MgO		1.13
SO_3	$\leq$ 4.0	3.09
Loss on Ignition	$\leq$ 5.0	1.29
Cl-	$\leq$ 0.10	0.0429
Na_2O / K_2O		0.28/0.78
Indeterminable content		0.96
S.CaO-Free Lime		1.6
C_3S		55.8
C_2S		18.50
C_3A		6.90
C_4AF		11.40
LSF		0.95

Table 3.2. Mechanical properties of cement.

COMPRESSIVE STRENGTH REQUIREMENTS TEST METHOD: TS EN 196-1		
Mechanical characteristic (days)	Standard Limits (MPa)	Test Results (MPa)
Early Strength (2 days)	≥ 20.0	28.3
Early Strength (7 days)	− − − − −	44.7
Standard Strength (28 days)	≥ 42.5 - ≤ 62.5	57.2

Table 3.3. Physical properties of cement.

PHYSICAL REQUIREMENTS TEST METHOD: TS EN 196-3 and TS EN 196-6		Standard Limits	Test Results
Specific Gravity (g/cm^3)			3.14
Setting Time (Vicat)	Initial (minutes)	≥ 60	110
	Final (minutes)	-	166
Soundness (Le Chatelier)(mm)		≤ 10	1
Fineness	Specific Surface (cm^2/g)	-	3690
	Residue on 45 μm sieve (%)		5.2
	Residue on 90 μm sieve (%)		0.3

3.1.2. Aggregates

Two types of coarse aggregates, natural and crushed sand were used and the proportions of aggregates were kept constant in all mixtures with the same amount of cement content. Physical properties of aggregates are listed in Table 3.4. The results of the performed aggregate sieve analysis were shown in Table 3.5.

Table 3.4. Physical properties of aggregates.

Aggeragate Type	Unit Weight (g/cm$_3$)	Water Absorption (%)
Coarse Aggregate (No 1)	2.71	0.6
Coarse Aggregate (No 2)	2.71	0.6
Crushed Sand	2.70	1.2
Natural Sand	2.61	0.9

Table 3.5. Gradation of aggregates.

	Sieve Size (mm)							
Aggeragate Type	**31.5**	**16**	**8**	**4**	**2**	**1**	**0.5**	**0.25**
Coarse Aggregate (No 1)	100	100	61.2	2.1	1	1	1	0.6
Coarse Aggregate (No 2)	100	100	61.2	2.1	1	1	1	0.6
Crushed Sand	100	100	100	100	99.8	99.7	96.1	31.4
Natural Sand	100	100	99.6	91.1	67	50.2	34.4	24.9
Mixture	100	88	65	48	42	38	34	14

3.1.3. Chemical admixtures

In the study, three types of superplasticizers were used which are vinyl copolymer (VC), sodium ligno-sulphonate (LS) condensation and naphtalene-sulphonate (NS) condensation based admixtures. The physical and chemical properties of the superplasticizers are given in Table 3.6.

Table 3.6. Physical and chemical properties of the superplasticizers.

	Test Results				Test Method
	VC	**LS**	**NS**	**P**	**All**
Color	Brown	Brown	Brown	Opaque	Observation
State	Liquid	Liquid	Liquid	Liquid	Observation
Specific Gravity(kg/l)	1.132	1.18	1.166	1.093	TS 781
pH	7.41	8.46	6.09	7.23	TS 6365
Chloride Content (%)	0.0253	0.0305	0.022	< 0.1	TS EN 480-10
Solid Content (%)	27.23	36.33	30.36	31.6	TS EN 480-8
Alkali content (%)	< 6	< 6	< 6	< 3	TS EN 480-6

3.1.4. Water

Tap water and magnetically treated water were used to produce concrete. Physical and chemical properties of tap water were analyzed by the Quality Laboratory of Akçansa Cement Factory as shown in Table 3.7. It is drinkable, clear and clean, and does not contain any substances at excessive amounts that can be harmful for making concrete according to TS EN 1008.

Table 3.7. Physical and chemical properties of tap water.

Parameters	**TS EN 1008 Limits**	**Test Results**
Total hardness (FR)	-	70
pH	>4	07.Haz
Total soluble content (mg/l)	-	48
Total alkalinity (mg/l)	-	100
Sulfate (mg/l)	2000	30
Cl- (mg/l)	500	110
Free chloride(Cl_2)	-	< 0.1
Sodium Eq.Alkali (mg/l)	1500	90.8
PO4 (mg/l)	100	0
NO_3 (mg/l)	500	2
NO_2 (mg/l)	500	0.01
Amonium (mg/l)	-	0.1
Suspended solid content (mg/l)	<4	0.01

3.2. Concrete Mixture Properties

A statistical software called Minitab (version 16) was used to set the design of experiment and interpret the results. The factors of the experiment were;

(i) Magnetic treatment of water,
(ii) Magnetic treatment of admixture,
(iii) Admixture type,
(iv) Cement dosage.

The responses were;

(i) 28-day compressive strength of concrete,
(ii) Slump of concrete.

In Table 3.8, the design table of experiments is given. As seen in Table 3.8 the number of factors is four and the replication number is one. Each factor has different number of levels which were explained in the next section. There are also some other experiments which are shown in Table 3.10. These were not shown in the below table because of having different number of factors.

In Table 3.8 A, B,C and D are the letters which refer the factors and the numbers 1,2 and 3 are the levels of the factors. For example; A refers to "magnetic treatment of water" and 1 means "there is a treatment", 2 means "there is no treatment". This approach is same for the other factors.

3.2.1. Concrete Mixture

Concrete mixtures were produced in a pan mixer which has a capacity of 40 dm3. In production, first cement and aggregates were dry mixed and then $\frac{1}{2}$ volume of water was added to the mixture. The superplasticizer was put into the rest of the water and this mixture was poured gradually into the pan mixer. The reason why half of the water was poured before adding superplasticizer is to prevent the absorption of admixture by aggregates. Otherwise, the effects of superplasticizers can be decreased. The process of concrete production took nearly 5 minutes. The concrete mixtures were casted in 10cm$x$10cm$x$10cm cube molds, 10cm$x$20cm cylinder molds and 15cmx15cmx15cm cubic molds according to TS EN 12390-2.

The variables were:

- Cement content (290 kg/m^3 or 300 kg/m^3),
- Admixture types (VC or LS or NS or P),
- Magnetic treatment of admixture and water(treated or untreated).

These differences were used to code the mixtures that are given in Table 3.10. For example: N29MVC means that the water is not magnetically treated(N), the cement content in the mixture is 290 kg(29), the admixture is magnetically treated (M) and admixture VC is used. The code is composed of 4 parts and the codes for each mixture are given in Table 3.10. The definitions of letters and numbers in the codes are explained in Table 3.9.

Table 3.8. Multilevel factorial design of experiments.

Multilevel Factorial Design					
Factors: 4	**Replicates: 1**				
Base runs: 24	**Total runs: 24**				
Base blocks: 1	**Total blocks: 1**				
Number of levels:	2	2	2	3	
Design Table					
Run	Blk	A	B	C	D
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	1	3
4	1	1	1	2	1
5	1	1	1	2	2
6	1	1	1	2	3
7	1	1	2	1	1
8	1	1	2	1	2
9	1	1	2	1	3
10	1	1	2	2	1
11	1	1	2	2	2
12	1	1	2	2	3
13	1	2	1	1	1
14	1	2	1	1	2
15	1	2	1	1	3
16	1	2	1	2	1
17	1	2	1	2	2
18	1	2	1	2	3
19	1	2	2	1	1
20	1	2	2	1	2
21	1	2	2	1	3
22	1	2	2	2	1
23	1	2	2	2	2
24	1	2	2	2	3

Table 3.9. The definition of coding procedure.

Water Treatment	Cement content	Admixture Treatment	Admixture Type
N: not magnetically treated	29: 290 kg of cement in 1 m^3	N: not magnetically treated	WA: no admixture
M: magnetically treated	30: 300 kg of cement in 1 m^3	M: magnetically treated	VC: vinyl copolymer
	44: 300 kg of cement in 1 m^3		LS: sodiumligno-sulfphonate
			NS: naphtalene-sulfphonate
			P: polycarboxylic ether

Table 3.10. Coding of concrete mixtures.

No	Water/Cement	Magnetic Treatment of Water	Cement content (kg/m^3)	Magnetic Treatment Of Admixture	Admixture Type	Code
1	0.6	N	290	-	-	N29WA
2	0.6	M	290	-	-	M29WA
3	0.6	N	300	-	-	N30WA
4	0.6	M	300	-	-	M30WA
5	0.6	N	290	N	VC	N29NVC
6	0.6	M	290	N	VC	M29NVC
7	0.6	N	290	M	VC	N29MVC
8	0.6	M	290	M	VC	M29MVC
9	0.6	N	300	N	VC	N30NVC
10	0.6	M	300	N	VC	M30NVC
11	0.6	N	300	M	VC	N30MVC
12	0.6	M	300	M	VC	M30MVC
13	0.6	N	290	N	LS	N29NLS
14	0.6	M	290	N	LS	M29NLS
15	0.6	N	290	M	LS	N29MLS
16	0.6	M	290	M	LS	M29MLS
17	0.6	N	300	N	LS	N30NLS
18	0.6	M	300	N	LS	M30NLS
19	0.6	N	300	M	LS	N30MLS
20	0.6	M	300	M	LS	M30MLS
21	0.6	N	290	N	NS	N29NNS
22	0.6	M	290	N	NS	M29NNS
23	0.6	N	290	M	NS	N29MNS
24	0.6	M	290	M	NS	M29MNS
25	0.6	N	300	N	NS	N30NNS
26	0.6	M	300	N	NS	M30NNS
27	0.6	N	300	M	NS	N30MNS
28	0.6	M	300	M	NS	M30MNS
29	0.6	N	300	N	VC	N30NVC2
30	0.58	M	300	N	VC	M30NVC2
31	0.38	N	440	N	P	N44NP
32	0.37	M	440	N	P	M44NP

In Table 3.11 mixture proportions are given. As seen on the table, the proportions of aggregates and the amount of admixtures are constant in mixtures with the same cement content.

Table 3.11. Mixture proportions.

		Content (kg/m^3)					
	Code	No 1	No 2	Sand	Crushed Stone	Water	Admixture
1	N29WA	481	481	486	465	178	-
2	M29WA	481	481	486	465	178	-
3	N30WA	475	475	480	459	184	-
4	M30WA	475	475	480	459	184	-
5	N29NVC	481	481	486	465	178	4.35
6	M29NVC	481	481	486	465	178	4.35
7	N29MVC	481	481	486	465	178	4.35
8	M29MVC	481	481	486	465	178	4.35
9	N30NVC	475	475	480	459	184	4.50
10	M30NVC	475	475	480	459	184	4.50
11	N30MVC	475	475	480	459	184	4.50
12	M30MVC	475	475	480	459	184	4.50
13	N29NLS	481	481	486	465	178	4.35
14	M29NLS	481	481	486	465	178	4.35
15	N29MLS	481	481	486	465	178	4.35
16	M29MLS	481	481	486	465	178	4.35
17	N30NLS	475	475	480	459	184	4.40
18	M30NLS	475	475	480	459	184	4.50
19	N30MLS	475	475	480	459	184	4.50
20	M30MLS	475	475	480	459	184	4.50
21	N29NNS	481	481	486	465	178	4.35
22	M29NNS	481	481	486	465	178	4.35
23	N29MNS	481	481	486	465	178	4.35
24	M29MNS	481	481	486	465	178	4.35
25	N30NNS	475	475	480	459	184	4.50
26	M30NNS	475	475	480	459	184	4.50
27	N30MNS	475	475	480	459	184	4.50
28	M30MNS	475	475	480	459	184	4.50
29	N30NVC2	475	475	480	459	184	4.50
30	M30NVC2	475	475	480	459	178	4.50
31	N44NP	510	220	550	490	167	6.60
32	M44NP	510	220	550	490	162	6.60

3.2.2. Concrete Test Specimens

For testing compressive strength a total of 6 cube specimens with dimensions of 10cm x 10cm x 10cm were casted for each mixture. Three of them were used for 7-day compressive strength test and 3 of them were used for 28-day compressive strength test. To test water penetration under pressure 3 cube specimens with dimensions of 15cm x 15cm x 15cm and for rapid chloride penetration test only one cylinder specimen with dimensions of 10cm x 20cm were casted for selected mixtures for the sake of time. On the whole 192 small cube specimens and 24 cylinder specimens were casted for compressive strength, 48 conventional cube specimens were casted for water penetration test under pressure and 12 cylinder specimens were casted for rapid chloride penetration test as shown in Table 3.12.

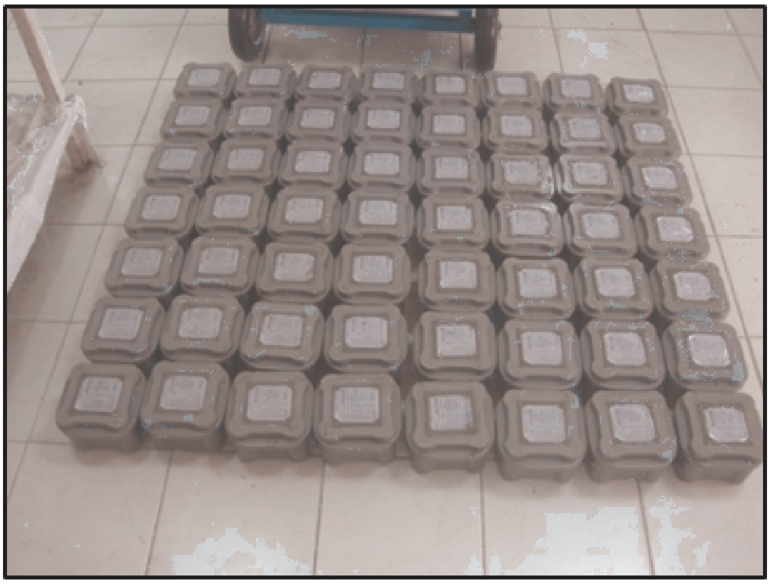

Figure 3.1. Cube specimens sized 10cm x 10cm x 10cm.

Figure 3.2. Casting of concrete in molds.

Table 3.12. The dimension and number of specimens.

	Cube specimens, 10cm x 10cm x 10cm			Cube specimens, 15cm x 15cm x 15cm	Cylinder specimens, 10cm x 20cm
	Code	Compressive Strength (7 days)	Compressive Strength (28 days)	Water Penetration Test Under Pressure	Rapid Chloride Penetration Test
1	N29WA	3	3	-	-
2	M29WA	3	3	-	-
3	N30WA	3	3	-	-
4	N30WA	3	3	-	-
5	N29NVC	3	3	3	1
6	M29NVC	3	3	3	1
7	N29MVC	3	3	3	1
8	M29MVC	3	3	3	1
9	N30NVC	3	3	-	-
10	M30NVC	3	3	-	-
11	N30MVC	3	3	-	-
12	M30MVC	3	3	-	-
13	N29NLS	3	3	-	-
14	M29NLS	3	3	-	-
15	N29MLS	3	3	-	-
16	M29MLS	3	3	-	-
17	N30NLS	3	3	-	-
18	M30NLS	3	3	-	-
19	N30MLS	3	3	-	-
20	M30MLS	3	3	-	-
21	N29NNS	3	3	-	-
22	M29NNS	3	3	-	-
23	N29MNS	3	3	-	-
24	M29MNS	3	3	-	-
25	N30NNS	3	3	3	1
26	M30NNS	3	3	3	1
27	N30MNS	3	3	3	1
28	M30MNS	3	3	3	1
29	N30NVC2	3	3	-	-
30	M30NVC2	3	3	-	-
31	N44NP	3*	3*	-	-
32	M44NP	3*	3*	-	-

4. EXPERIMENTAL PROCEDURES

4.1. Experiments on Water

Experiments on water were carried out at several laboratories. *pH* and FTIR analyses were conducted at Akçansa Cement laboratory. Surface tension, viscosity, O-NMR and H-NMR analyses were conducted at laboratories of Sabancı University Engineering Department.

4.1.1. Magnetic Treatment of Water

A PVC pipe which was surrounded by 24 permanent neodymium magnets was used to magnetically treat the water and the admixtures as shown in Figure 4.1. Power of each magnet is 1 Tesla. The magnets were located in 6 groups with a distance of 5 cm as creating a magnetic field perpendicular to the flow direction as shown in Figure 4.2. The flow rate was fixed at a value of 0.12 l/s.

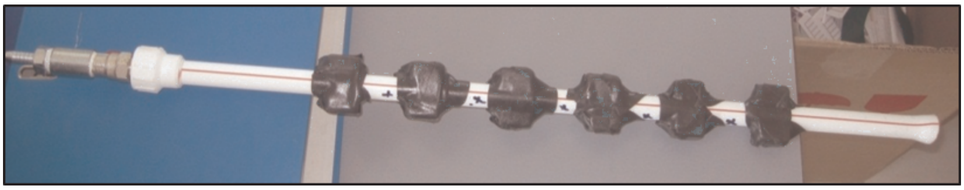

Figure 4.1. Magnetic treatment apparatus.

The water and admixture were poured into the pipe steadily. The direction of flow is perpendicular to the magnetic field as seen in Figure 4.3. The flow rate was constant as the valve at the end of the pipe was fixed. The magnetically treated water and admixture were used immediately after the preparation process.

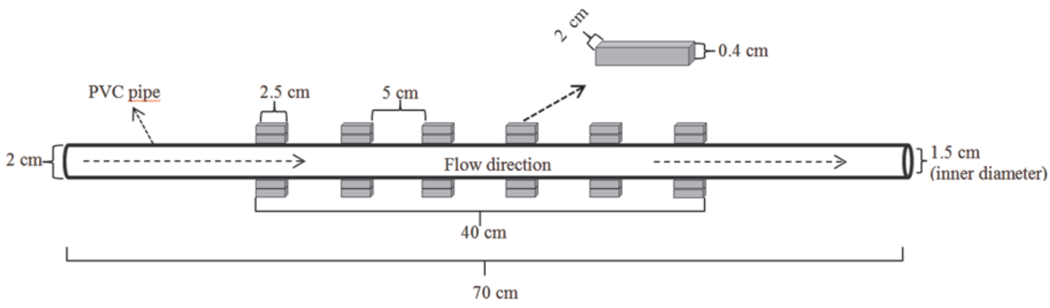

Figure 4.2. Dimensions of the treatment device.

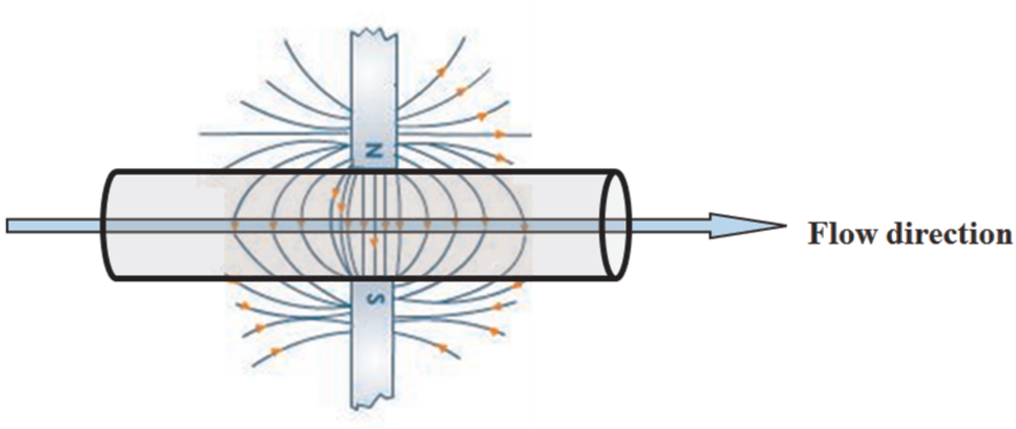

Figure 4.3. Direction of water flow and magnetic fields.

4.1.2. Surface Tension

To measure the surface tension of water "drop shape method" was selected. It is also called pendant drop method. It is a simple method and depends on the geometry of drop as shown in Figure 4.4. German made Krüss DSA 10-Mk2 device was used for the analysis.

The water sample was loaded in a syringe with a capacity of 250 μl. The diameter of the needle was 0.5 mm. The capacity of syringe and the diameter of the needle were entered to the software to calibrate the pump. After getting a drop, magnification was adjusted and the shape and clarity of drop on the screen was checked as seen in Figure 4.5 and Figure 4.6.

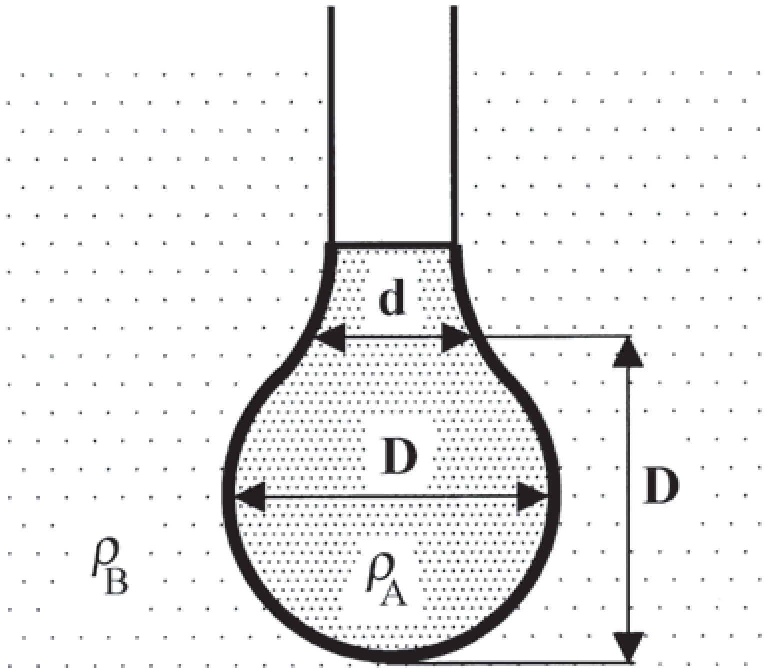

Figure 4.4. The geometry of pendant drop.

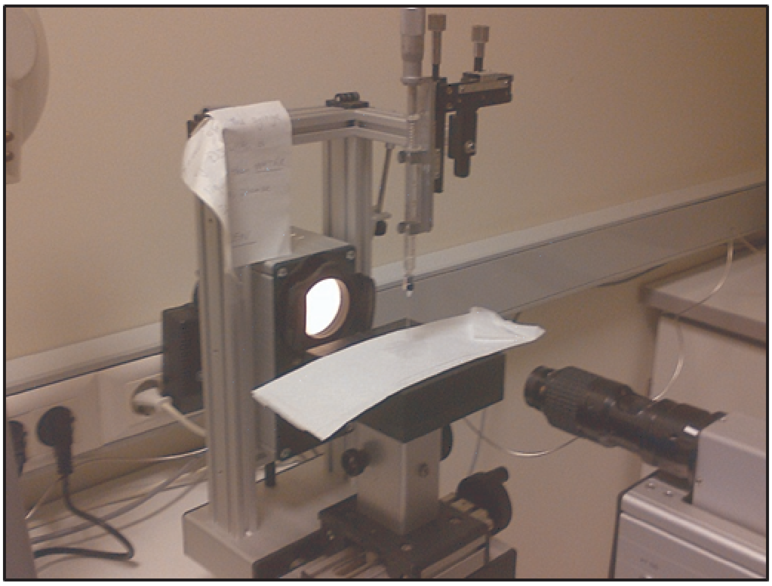

Figure 4.5. Magnification and recording of water drop.

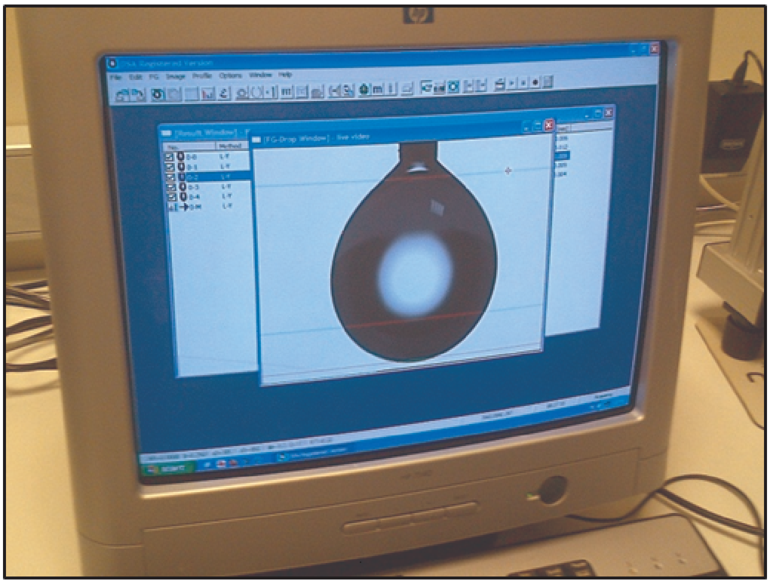

Figure 4.6. The image of drop on the screen.

The software can automatically calculate the volume of drop, angle of drop, diameter and height of drop, shape factor of drop and the surface tension of the liquid. The formula of surface tension is below [65]:

$$ST = \frac{\Delta p.g.D^2}{H} \tag{4.1}$$

where [ST] is the Surface tension of liquid (mN/m), [Δp] is the Pressure of the drop, [g] is the gravity force, [D] is the Diameter of the drop, [H] is the Shape dependent parameter.

4.1.3. Viscosity

To measure the viscosity of water, Ubbelohde Dilution Viscometer with an accuracy of ±0.1% was used. It is generally useful for measuring the viscosity of transparent Newtonian liquids. It can measure the same viscometer constant at all temperatures [66]. The test setup is shown in Figure 4.7. The apparatus of the test are Ubbleohde viscometer as shown in Figure 4.8., viscometer holder, temperature-controlled bath, thermometer and timer. The test was performed according to ASTM D2857.

Before the test, the viscometer was cleaned with a solvent and then with filtered air. 50 ml of water was put into tube 1 up to the lower filling line as shown in Figure 4.9. It was checked whether the water went above the upper filling line or not when the viscometer was brought to the vertical position. The U-tube was filled completely at the bottom to prevent the formation of air bubbles. The viscometer was positioned in a thermostat maintained at 25°C for 10 minutes to thermally equilibrate. Then, a plug was placed over tube 3 and suction was applied to tube 2 as shown in Figure 4.10, until the liquid reached the center of the bulb C. The suction was disconnected from tube 2 and the plug was removed from tube 3 and was immediately placed over tube 2 until sample dropped away from the lower end of the capillary. The plug was removed and the efflux time was noted. This test was performed for both tap water and magnetically treated water.

The relative viscosity was measured by calculating the ratio of average efflux time of tap water and magnetically treated water by using the equation 4.2, equation **??** and equation **??** shown below.

$$t_{analysis} = \eta_{analysis}/c_{analysis} \tag{4.2}$$

$$t_{reference} = \eta_{reference}/c_{reference} \tag{4.3}$$

$$\eta_{relative} = \eta_{analysis}/\eta_{reference} \tag{4.4}$$

where $[\eta_{relative}]$ is the Relative viscosity, $[t_{analysis}]$ is the Efflux time for magnetically treated water, $[t_{reference}]$ is the Efflux time for tap water, $[c_{analysis}]$ is the Concentration of analysis, $[c_{reference}]$is the Concentration of reference.

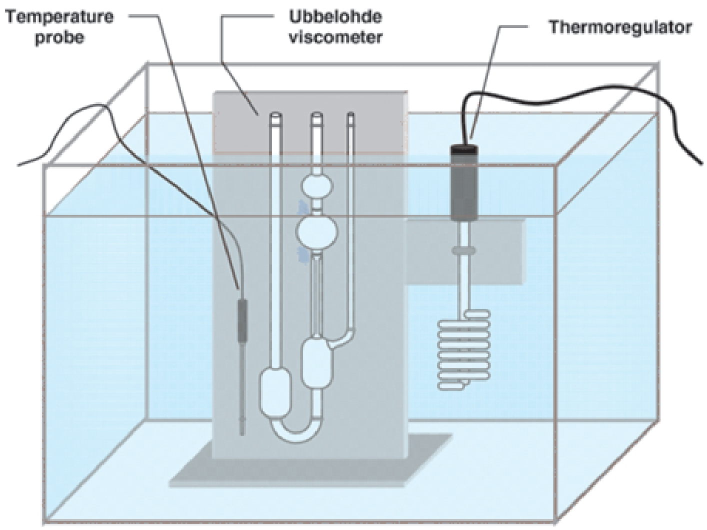

Figure 4.7. The Ubbelohde viscometer in a thermostat.

Figure 4.8. Ubbelohde viscometer.

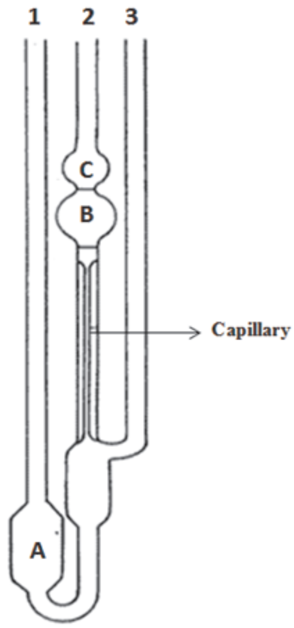

Figure 4.9. Sections of Ubbelohde viscometer.

Figure 4.10. Suction of water in the viscometer.

4.1.4. pH

The *pH* of water was measured by WTW InoLab 720 *pH* Meter as shown in Figure 4.11. 5 samples of tap water and magnetically treated water were prepared and put inside a glass beaker. Before measuring, the probe was cleaned by distilled water.

The temperature of water was 20 ±0.5^{o}C.

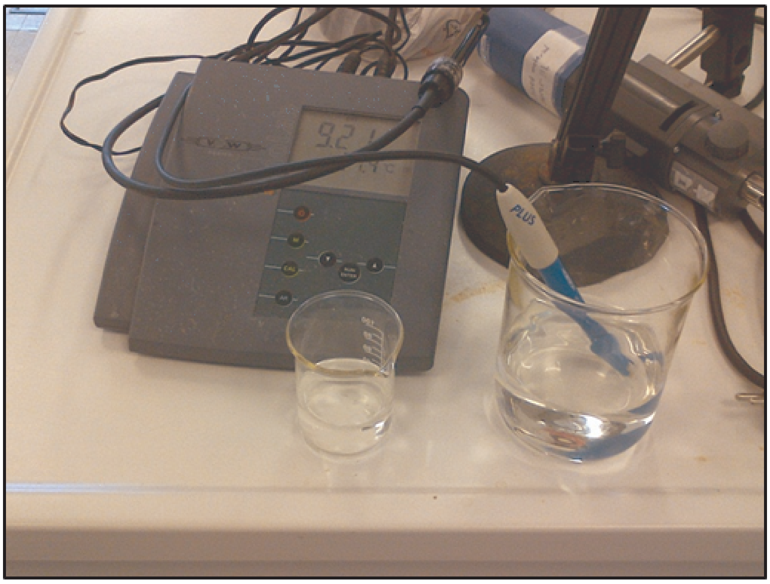

Figure 4.11. Measuring of pH of magnetically treated water.

4.1.5. Fourier Transform Infrared Spectroscopy Analysis (FTIR)

Tap water, magnetically treated water and distilled water samples were analyzed at a German made Bruker Alpha FTIR spectrometer as shown in Figure 4.12. The temperature of samples was 20±0.2^{o}C. Drop of each samples were put on the disc of the spectrometer. The correlation between the samples was automatically calculated by the software. The unknown compounds and amount of compounds in water can be identified by FTIR analysis. Software can compare the different mixtures and calculate the correlation between them.

Figure 4.12. Fourier Transform Infrared Spectrometer.

4.1.6. H-NMR Analysis

H-NMR analysis of tap and magnetically treated water and distilled water samples were analyzed at 500 MHz Varian superconducting NMR spectrometer. 10 mg of samples were put into a cleaned glass tube. 0.75 mL of deuterium was added to the samples as a solvent. The height of the sample in the glass tube should be at least 4.5 cm. The mixture was shaken to make it homogeneous. The mixture should not be blurry. After all each tube was labeled and top of the tubes were closed with a teflon cap. Then a tube was inserted inside the NMR spectrometer. Because of the magnetic field while moving close to the NMR spectrometer to carry metallic equipment or accessories such as pencil or watch can be dangerous. So during the analysis, occupational safety regulations were obeyed.

The analysis for each sample took half an hour and the results were obtained by the software program.

4.1.7. O-NMR Analysis

O-NMR analysis of tap and magnetically treated water and distilled water samples were analyzed at 500 MHz Varian superconducting NMR spectrometer. 10 mg of samples were put into a cleaned glass tube. In this analysis no solvent was needed. The height of the sample in the glass tube should be at least 4.5 cm. The mixture was shaken to make it homogeneous. After all each tube was labeled and top of the tubes were closed with a teflon cap. Then a tube was inserted inside the NMR spectrometer.

It is similar to H-NMR analysis. By the software program the results were obtained. Duration of the test is shorter than H-NMR analysis.

4.2. Fresh Concrete Properties

4.2.1. Slump Test and Slump Retention Test

Slump test was performed to determine the workability of concrete mixtures according to TS EN 12350-2. The concrete mixture was put into the slump test cone as in three layers with equal volumes. Each layer was compacted with 25 strokes of the tamping rod. The mold was raised upward in 3-5 seconds. The distance between the top of the mold and the highest point of the slumped test specimen was measured.

In the study, any specific slump value was not targeted, because the slump value was a performing criterion.

Slump retention test was performed to compare the effect of magnetization on different mixtures. After slump test, the mixtures were kept in a container for an hour. Then the mixture was put into the pan mixer and remixed again. Slump test for each mixtures were performed again.

Before the test to evaluate the effect of operators on slump test Gage R and R analysis was performed. Gage R and R (Gage Repeatability and Reproducibility) is the amount of measurement variation introduced by a measurement system, which consists of the measuring instrument itself and the individuals using the instrument. A Gage R and R study quantifies the analysis below;

(i) Repeatability - variation from the measurement instrument,
(ii) Reproducibility - variation from the individuals using the instrument,
(iii) Overall Gage R and R, which is the combined effect of (1) and (2).

According to the result of analysis it can be concluded if the measurement method, equipment's calibration and operator accuracy is sufficient or not.

Two operators measured slump of 6 concrete mixtures. All the mixtures were produced with the same amount and quality of constituents. They were all same. Each operator measures the slump value twice for each mixture. The analysis table is shown in Table 4.1.

Table 4.1. Slump values measured by operators for each part.

RunOrder	**Parts**	**Operators**	**Slump**	**RunOrder**	**Parts**	**Operators**	**Slump**
1	1	1	21	13	1	1	20.5
2	1	2	21	14	1	2	21
3	2	1	20.5	15	2	1	21
4	2	2	21	16	2	2	21
5	3	1	20.5	17	3	1	21
6	3	2	21	18	3	2	20.5
7	4	1	21	19	4	1	21
8	4	2	21	20	4	2	21
9	5	1	20.5	21	5	1	20.5
10	5	2	20.5	22	5	2	21
11	6	1	21	23	6	1	20
12	6	2	20.5	24	6	2	20

Variation report of the Gage R and R analysis is shown in Figure 4.13. The summary of this report is given in Figure 4.14. As a result the total variation of a measurement should not be greater than 30%. This means something wrong in measurement.

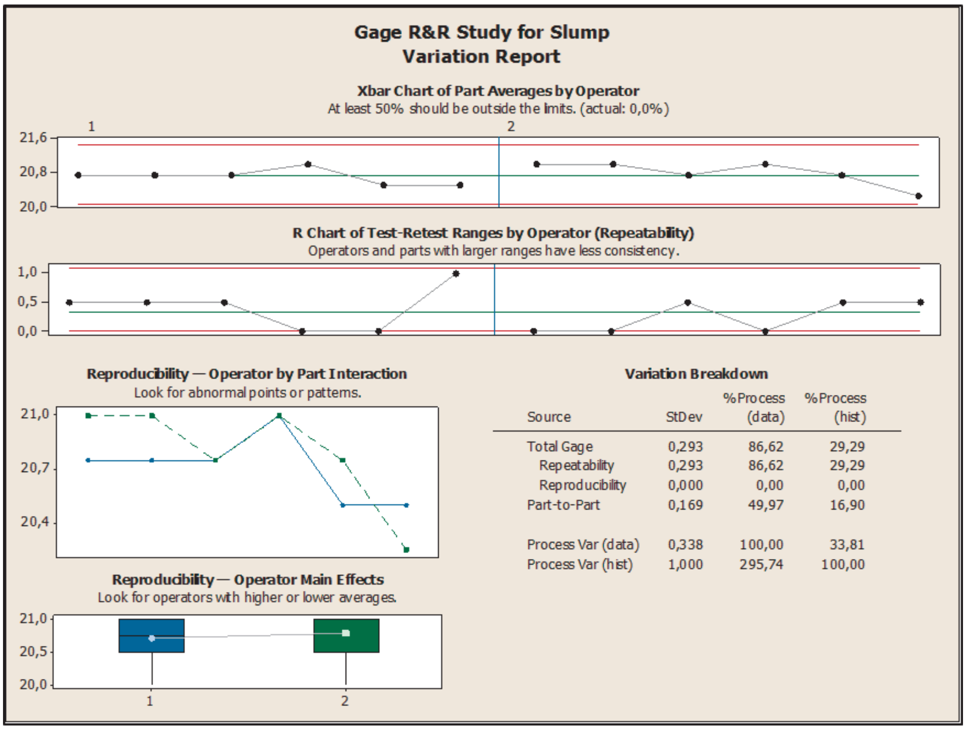

Figure 4.13. Variation report of Gage R and R analysis.

As seen in Figure 4.14 total variation of the measurement is 29.3%. It is between marginal zone. This means the measurement is not unacceptable but there can be some improvements to make it more accurately.

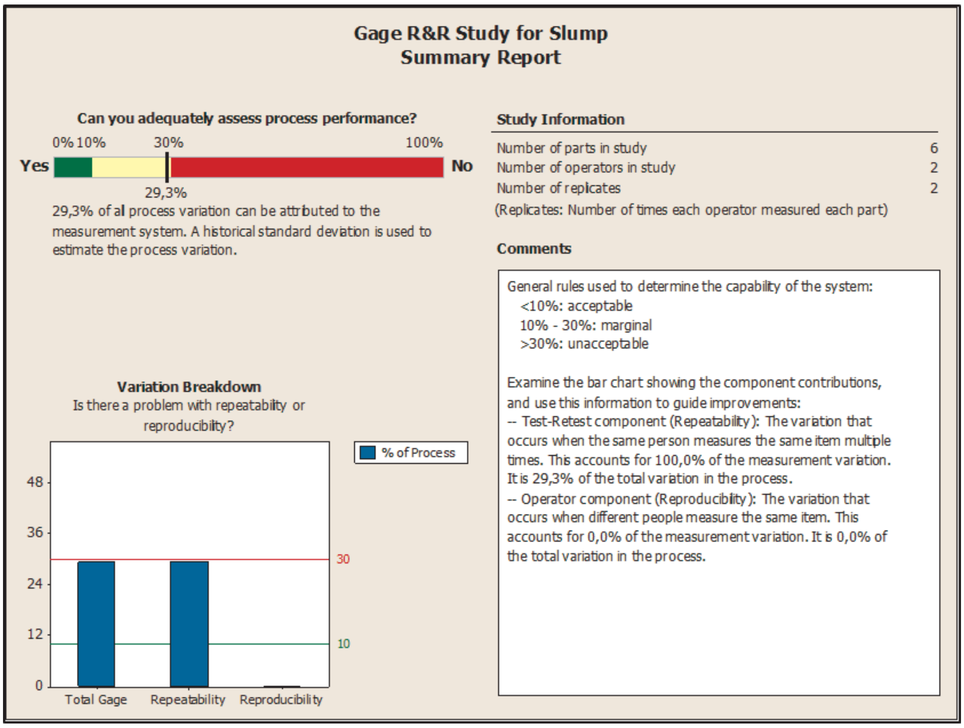

Figure 4.14. Summary report of Gage R and R analysis.

This study was a pre-control study before doing experiments. It was decided to keep the operators and measurement method same. The standard deviation of historical measurements was assumed as 1.0. The standard deviation of the pre-control study was 0.338 which is better.

4.2.2. Density of Concrete

Density of concrete was measured according to TS EN 12350-6. A cube mold with dimensions of 10cmx10cmx10cm was used as a container. After weighting the empty mold, it was filled with concrete in two layers. Each layer was compacted on the vibrating table. Then the weight of the mold with concrete was again measured. The density of concrete was calculated by dividing the net weight of the concrete by the volume of the mold.

4.3. Mechanical Properties of Concrete

Compressive strength test on specimens at the age of 7 days and 28 days were performed according to TS EN 12390-3. Before the test, all the specimens were kept in molds for one day and then cured in water for 27 days according to TS EN 12390-2. The curing temperature was fixed at 20^{o}C. The specimens were taken out from the curing container and they were kept in air. When the surface of the specimens was dry, the compressive strength test was performed. The press machine with a capacity of 3000kN (300 tons) was used and the loading rate was 0.6MPa/s according to TS EN 12390-4.

4.4. Durability of Concrete

To investigate the effect of magnetically treated water on durability of concrete, rapid chloride ion permeability test and water penetration under pressure test were conducted.

4.4.1. Rapid Chloride Permeability Test

The test was performed according to ASTM C1202-12. The test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. For the test, 10cmx20cm cylinder specimens were casted and cured in water for 27 days. The specimens were sawn cut to get slices with a thickness of 5 cm and a diameter of 10 cm. The rough surface of the test specimen was coated with rapid setting epoxy. After the coating was dried, the specimen was saturated with water and then soaked for 18 hours in deaerated water in vacuum desiccators with a vacuum pump as seen in Figure 4.15. After 18 hours, the specimens were placed in the testing apparatus as seen in Figure 4.16. A potential difference of 60V DC was maintained across the ends of the specimens. One surface of the specimen was immersed in a sodium chloride solution and the other one was in a sodium hydroxide solution as shown in Figure 4.17. The current passing through the specimens was measured manually at least at every 30 minutes during 6 hours as shown in Figure 4.18. As the chloride ions penetrated into the concrete, the pore solution became more conductive and the current readings increased. The total charge passing through the specimen was found by calculating the total area under the plot of time versus current.

Figure 4.15. Soaking of concrete specimen in the desiccator.

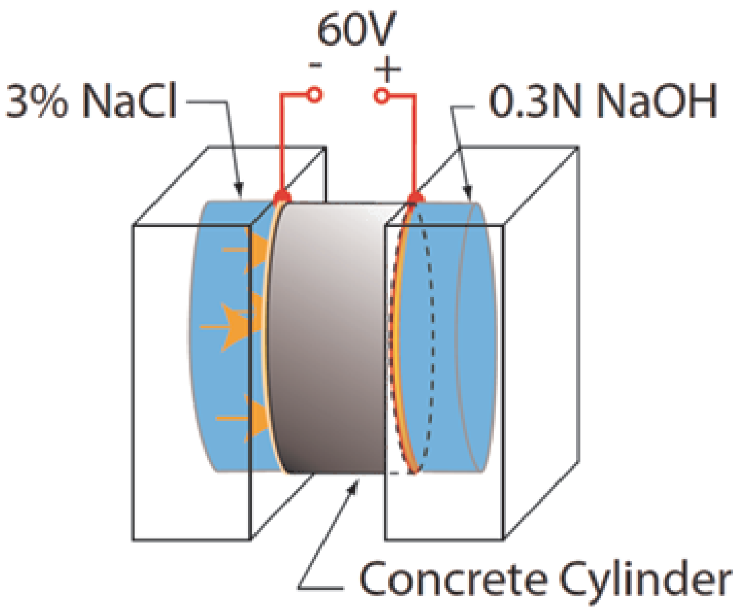

Figure 4.16. Schematic of rapid chloride permeability test setup [67].

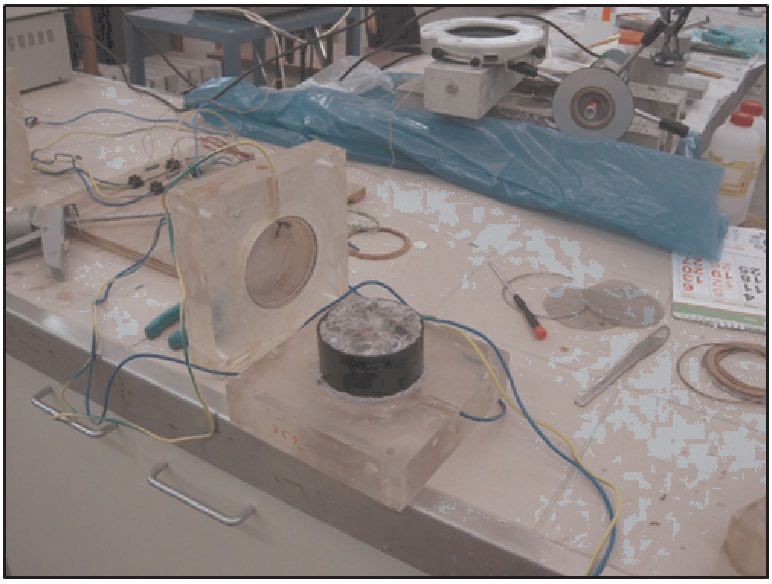

Figure 4.17. Preparation of samples for the test.

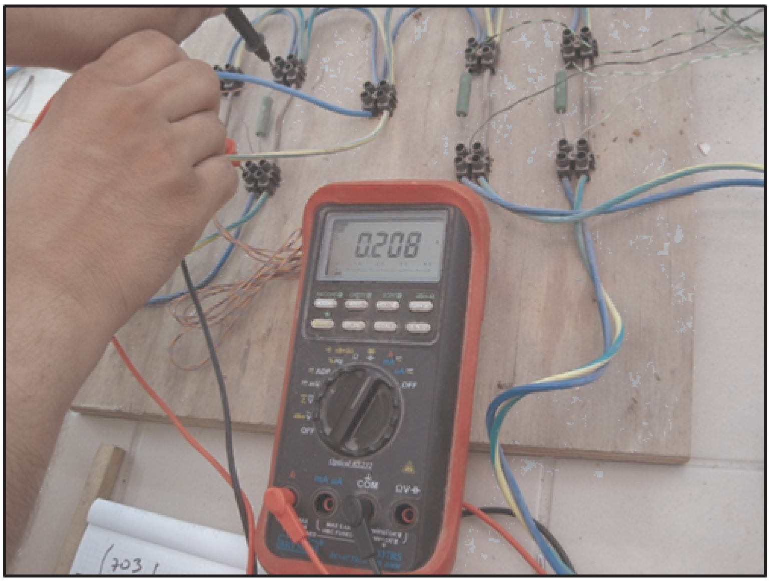

Figure 4.18. Reading of charge passing from each sample.

4.4.2. Water Penetration Test under Pressure

The cube specimens with dimensions of 15cmx15cmx15cm were tested to determine the water penetration under pressure according to TS EN 12390-8. The cube specimens were cured in water with a temperature of 20^{o}C for 27 days after de-molding according to TS EN 12390-2.

The specimens were placed in the testing apparatus and a pressure of 500kPa was applied to the smooth surfaces of the specimens for 72 hours. During the test, the appearance of the surfaces was observed periodically to control whether there was a leakage or not. After 72 hours, the specimens were removed from the apparatus and the surface exposed to pressure were wiped and dried. The specimen was split in half, perpendicular to the face on which the water pressure was applied. After splitting the specimen, the face of the specimen was observed and the water front on the specimen was marked as shown in Figure 4.19. The maximum depth of water penetration under the test area was measured and recorded to the nearest mm.

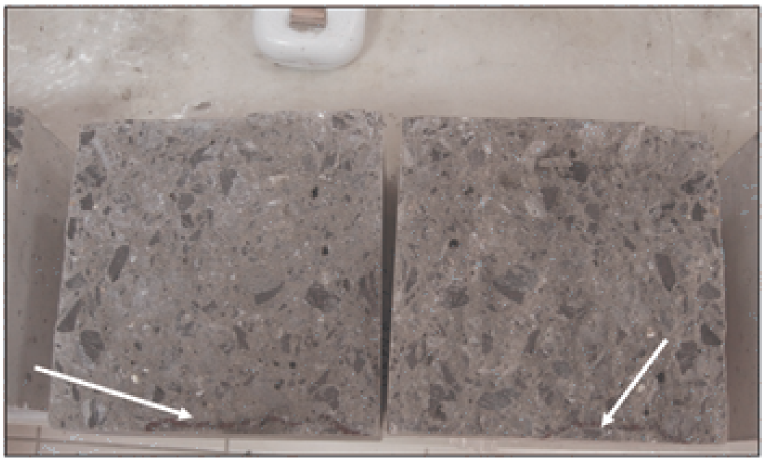

Figure 4.19. Measurement of maximum depth of water penetration.

5. RESULTS AND DISCUSSIONS

5.1. Experiments on Water

The results of surface tension, viscosity, pH, H-NMR, O-NMR and FTIR analysis of water were discussed in this section. It was aimed to understand and see the changes in micro properties of water before making comments on concrete properties.

5.1.1. Surface Tension

Surface tension analysis of tap water and magnetically treated water was conducted at Sabancı University. The analysis method was "pendant drop shape" method. Water, which was the same water used in concrete production and in other tests, was treated magnetically at the laboratory of Sabancı Universisty. The water exposed to magnetic field was analyzed very quickly.

The surface tension of tap and magnetically treated water (MT) are given in Table 5.1. For each type of water, the experiment was repeated twice as Trial 1 and Trial 2 by using different water samples. At each experiment, the analysis was run over 5 times with the same sample.

As seen in Table 5.2., the average value of surface tension of tap water is 76.1 mN/m and its standard deviation is 0.97. On the other hand, the average value of surface tension of magnetically treated water is 62.8 mN/m and its standard deviation is 1.32.

After magnetization of water, the surface tension was decreased approximately 17.5%. The measured surface tension of tap water is close to the value (72.8 mN/m) in literature as seen in Table 2.3.

Table 5.1. Surface tension and theta angle of tap and magnetically treated water.

Trial No	Run Over No	Water Type	Theta angle(degree)	Surface Tension (mN/m)
1	1	Tap	124.8	75.15
1	2	Tap	123.8	78.67
1	3	Tap	111.8	75.8
1	4	Tap	127.3	75.94
1	5	Tap	119.9	75.91
2	1	Tap	125.4	75.33
2	2	Tap	119.6	75.9
2	3	Tap	115.3	75.84
2	4	Tap	126.8	75.81
2	5	Tap	120.1	75.92
1	1	MT	140.4	63.45
1	2	MT	140.6	63.35
1	3	MT	136.5	61.55
1	4	MT	136.7	60.51
1	5	MT	138.1	63.18
2	1	MT	141.3	63.68
2	2	MT	140.6	63.41
2	3	MT	139.9	64.17
2	4	MT	137.2	60.98
2	5	MT	140	63.56

Table 5.2. The average values of surface tension of tap and magnetically treated water.

	Surface Tension (mN/m)	Standard Deviation
Trial 1-Tap water	76.29	1.37
Trial 1-Magnetically treated water	62.4	1.31
Trial 2-Tap water	75.76	0.24
Trial 2-Magnetically treated water	63.16	1.25
Tap water	76.1	0.97
Magnetically treated water	62.8	1.32

As shown in Table 5.3, almost all of the studies about surface tension of water and magnetically treated water reported that after magnetization the surface tension of water decreases. In this study, the difference is a bit higher than the studies in literature. The reasons of this situation may be the differences in properties of water and magnetization efficiency.

Table 5.3. Studies in literature about surface tension of water and magnetically treated.

	Surface Tension(mN/m)		
	Tap Water	Treated Water	Decrease %
Amiri *et al.*, [14]	71	65	8.5
Yang *et al.*, [16]	73	68.5	6.2
Cho *et al.*, [52]	73	69	5.5
Huo *et al.*, [53]	74.4	72.4	2.7

The reason in reduction of water surface tension when it is exposed to magnetic field is the change in its atomic structure. As known water is a polar molecule and each water molecules have a negative part and a positive part. The positive sides of a water molecule are attracted to the negative sides of a different water molecule and this attraction causes surface tension [98, 99]. So it can be said that the change in hydrogen bonds of water molecules lead to a change in surface tension of water. The change in surface tension of water is very important for wetting property of water. Liquids with low surface tension have a higher wetting property that is also called hydrophilic property. The change in water structure due to the decrease in surface tension will be explained in Part 5.1.5 and 5.1.6.

5.1.2. Viscosity

Viscosity measurement of tap water and magnetically treated water was conducted at Sabancı University. The samples were prepared at the laboratory. Ubblehode viscometer was used to measure the viscosity.

In Table 5.4, the efflux time of water which can represent the viscosity is shown. The test was repeated 3 times for both tap and treated water. The average efflux time of tap water is 13.2 seconds and treated water is 14.4 seconds. This means magnetically treated water resists flowing more than tap water.

Table 5.4. The efflux time of tap and magnetically treated water.

	Efflux Time (sec)	
No	Tap Water	Magnetically Treated Water
1	13.6	14.6
2	13.2	14.8
3	12.8	13.9
Average	13.2	14.4

The efflux time means the time of water passing through the Ubblehode viscometer. If the viscosity of water is high, the efflux time gets higher. Of course time is not a unit of viscosity but by comparing the efflux time a comparison between tap and treated water can be drawn. Ubblehode viscometer is not the best method for measuring water viscosity. It is better for polymers and samples with different concentrations.

It is known that the both viscosity and surface tension of water depends on the strength of hydrogen bonds [24, 37]. An increase in hydrogen strength can lead to an increase in viscosity as shown in Table 2.1 before.

Ghauri *et al.*, [55] reported that a relatively weak magnetic field can increase the viscosity of water, which can be interpreted by the stronger hydrogen bonds under the magnetic field.

5.1.3. pH value

The pH value of tap water and magnetically treated water was measured at Akcansa Cement Laboratory. The pH values of both tap and treated water are given in Figure 5.1. The test was repeated five times by using different samples. An increase in pH value was calculated in all readings. The average increase is nearly 2.2%.

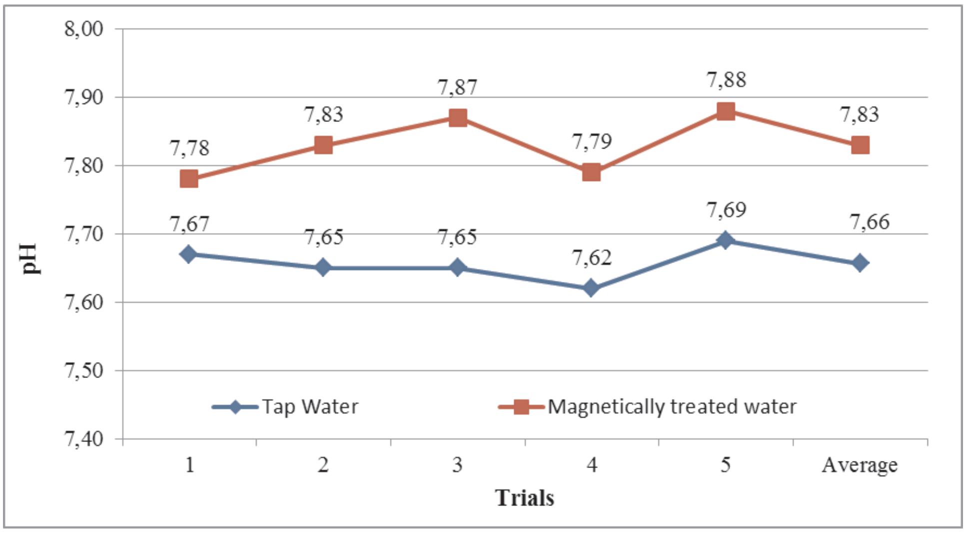

Figure 5.1. The pH values of tap and magnetically treated water.

The studies about this subject in literature are shown in Table 5.5. A slight increase in pH was found by the researchers.

Table 5.5. Studies in literature about the pH value of water and magnetically treated water.

	pH	
	Tap Water	Treated Water
AbdelTawab *et al.*,	7.73	7.74
Wang *et al.*,	7.52	7.61

The main reason of this change is probably the change in hydrogen bond strength and size of clusters. Toledo *et al.*, [42] stated that the magnetization leads to water molecules broken into smaller clusters and change the strength of hydrogen bonds. So this change can lead to an increase in pH of water. This situation is associated with the increase of OH^- ions concentration of water when it is exposed to magnetic treatment [68].

5.1.4. Fourier Transform Infrared Spectroscopy Analysis (FTIR)

FTIR analysis was conducted at Akcansa Cement Laboratory. FTIR analysis applied to tap water and treated water. As seen in Figure 5.2, there is no difference between the samples. The line seen in Figure 5.2 shows the amount of compounds. Each compound such as Cl^- , OH^-, Mg et.c has different frequencies. So it can be said that magnetic treatment does not change the amount of compounds in water.

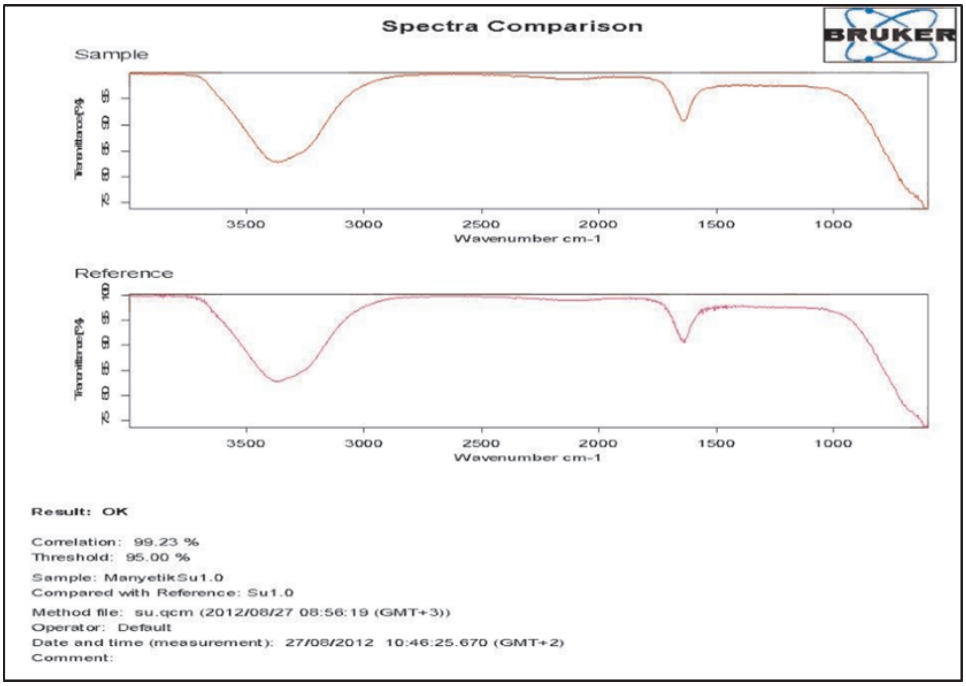

Figure 5.2. FTIR analysis of tap and magnetically treated water.

5.1.5. H-NMR Analysis of Water

H-NMR analysis was conducted at Sabancı University. T1 relaxation time which is also called spin-lattice relaxation time was measured for tap water and treated water. T1 time of magnetically treated water is 0.4377 second and this value is 0.2511 for tap water as seen in Figure 5.3 and Figure 5.4. Although there are a few studies about this subject in literature, the results support the theoretical acceptations.

As told before T1 time is an indicator of water cluster size. As T1 increases the size of water clusters decreases. In this study as seen in Figure 5.3 and Figure 5.4, T1 time is bigger for magnetically treated water. So it can be said that magnetization of water can change the molecular size of the clusters and water clusters get smaller. The change in cluster size can affect the hydration reaction between water and cement. It will be concluded at the end of Section 5.1.6.

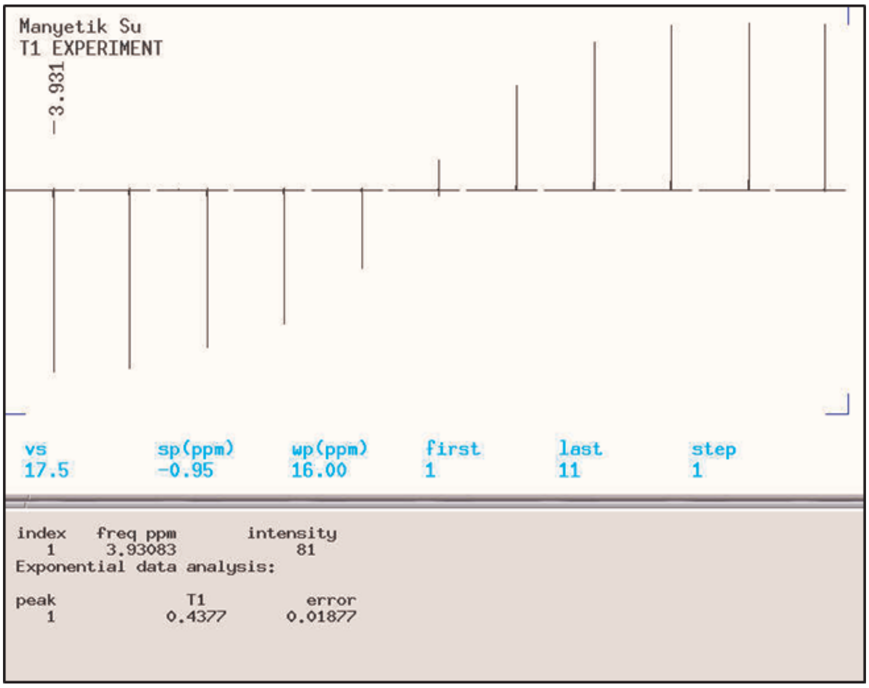

Figure 5.3. T1 time of magnetically treated water.

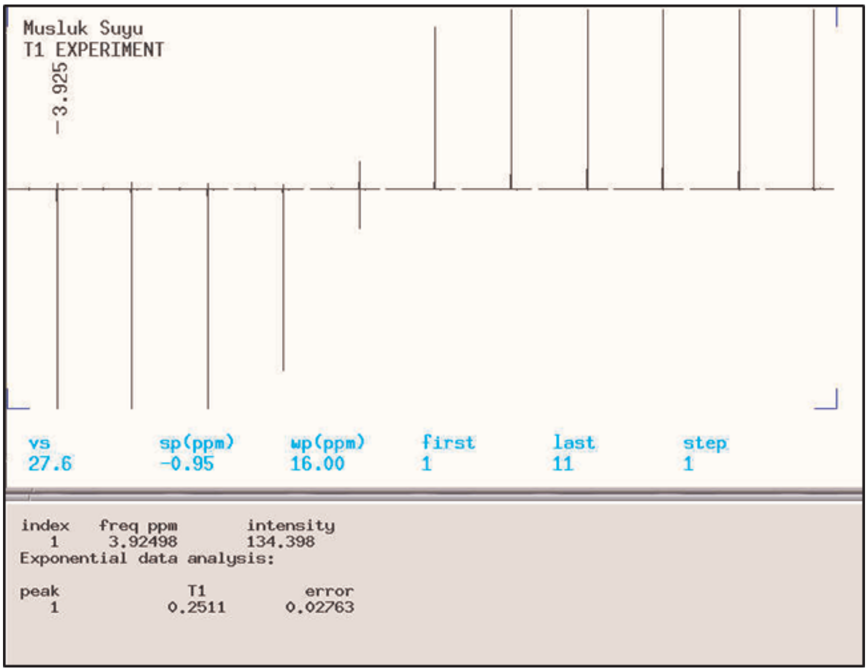

Figure 5.4. T1 time of tap water.

5.1.6. O-NMR Analysis of Water

O-NMR analysis was conducted at Sabancı Univeristy. The line-width of tap and treated water was measured by O-NMR analysis. The results are parallel to the studies in literature. The half-height width of peak of the tap water sample is 83.95 Hz and this value is 73.83Hz for the treated water as seen in Figure 5.5. The width of the parabola reflects the molecular size of the water clusters. As a result it can be said the cluster sizes are smaller when the water is exposed to a magnetic field.

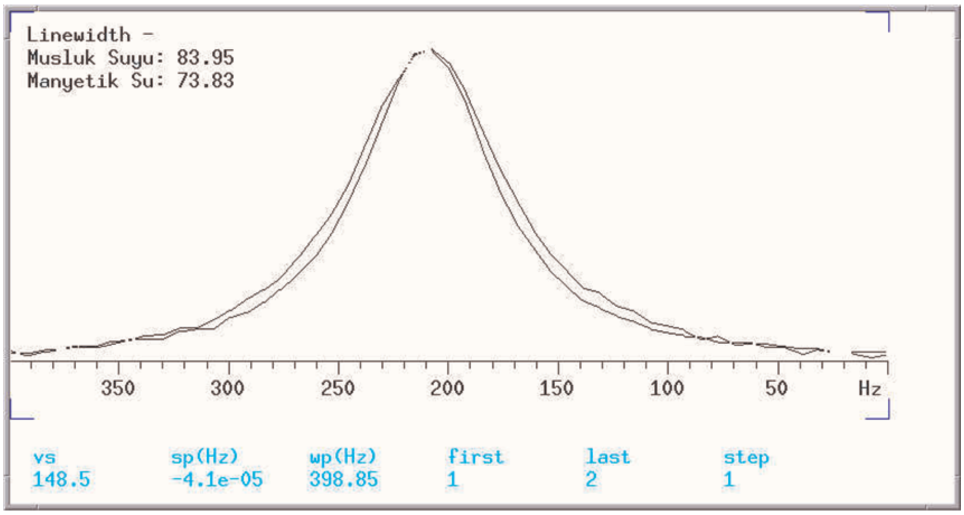

Figure 5.5. O-NMR analysis of tap and magnetically treated water.

After all tests on water, it is seen that when water was magnetically treated surface tension and half-height width of its frequency decreased and pH, viscosity and T1 relaxation time were found to be increased in this study. These results and what they lead to will be explained and evaluated together with the results of fresh and hardened concrete tests at the end of the chapter.

One of the problems is that small cluster water is not stable. The electric charges inherent in water continually cause the small clusters to bind together into larger and larger clusters. And to make matters worse, the process is accelerated when water is exposed to air and light [69].

5.2. Fresh Concrete Properties

Slump values of concrete mixtures are given in Table 5.6. and slump retention values are given in Figure 5.5. In this study, 4 types of concrete admixtures were used. The slump values of mixtures produced using different type of admixtures and cement dosage were different. Because the increase in cement dosage causes an increase in workability and the recipes of the admixtures are different so their effects are also different. So it is best to evaluate the results in groups with same cement dosage and same admixture.

Table 5.6. Slump of concrete mixtures.

	Code	Slump (cm)	Concrete Temperature (^{o}C)	Air Temperature (^{o}C)	Unit Weight, kg/m^3
1	N29WA	4	24.6	23.6	2388
2	M29WA	4	24.8	23.6	2375
3	N30WA	5	24.4	23.6	2394
4	M30WA	6	24.4	23.6	2380
5	N29NVC	16	23.0	22.1	2372
6	M29NVC	18.5	23.4	23.0	2382
7	N29MVC	18	23.0	22.1	2380
8	M29MVC	18	23.6	23.0	2390
9	N30NVC	20.5	23.4	23.0	2387
10	M30NVC	20.5	23.0	22.1	2384
11	N30MVC	20.5	23.4	22.1	2385
12	M30MVC	21	23.4	23.0	2377
13	N29NLS	17	23.6	23.1	2388
14	M29NLS	16	23.4	23.1	2383
15	N29MLS	17	23.5	23.0	2389
16	M29MLS	16.5	23.2	23.0	2375
17	N30NLS	20	23.4	23.1	2387
18	M30NLS	20	23.5	23.0	2383
19	N30MLS	19.5	23.6	23.0	2388
20	M30MLS	19	23.3	23.0	2379
21	N29NNS	19	24.5	23.6	2377
22	M29NNS	21.5	24.4	23.6	2380
23	N29MNS	22	24.4	23.6	2385
24	M29MNS	21.5	24.4	23.6	2390
25	N30NNS	21	23.0	22.1	2388
26	M30NNS	21.5	24.3	23.6	2390
27	N30MNS	21.5	24.2	23.6	2385
28	M30MNS	22	23.0	22.1	2384

As known the mix water and admixtures were magnetically treated and used in concrete production. It was aimed to investigate the effect of treated water, treated admixture and both on workability of concrete.

In Figure 5.6, the effect of magnetization of water on slump can be seen. The cement dosage of mixtures was 290 kg. The slump values of mixtures which did not contain any admixture were the same. No effect could be seen in slump when the water was magnetically treated for these mixes. On the other hand the slump values increased for the mixtures produced with VC and NS type of admixtures when treated water was used. The increase in slump for both mixtures is 2.5 cm. This increase is very impressive. Because to increase the slump value of concrete in that amount more admixture should be used. For this reason usage of treated water can be economic. The slump value of concrete produced with LS type of admixture decreased as 1 cm when treated water was used.

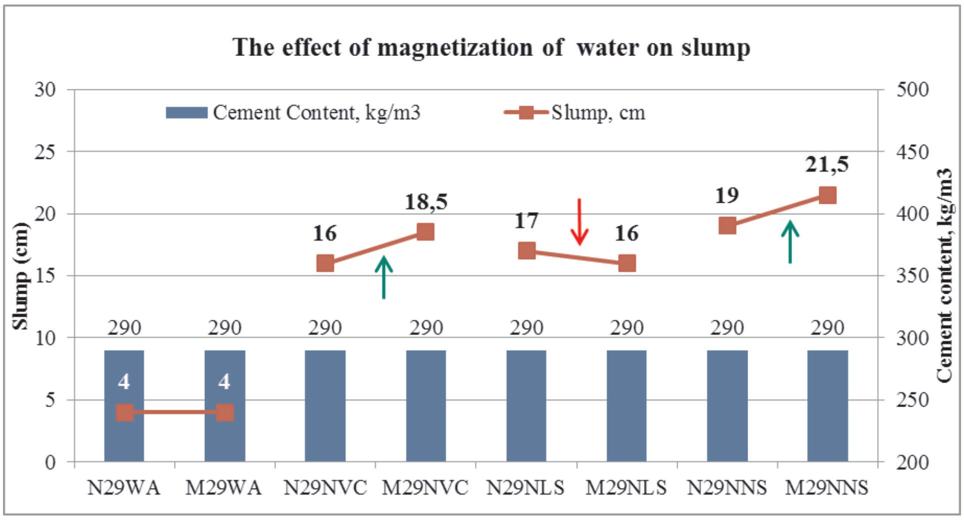

Figure 5.6. The effect of treated water on slump of concrete (290 kg cement dosage).

In Figure 5.7, the effect of magnetization of water on slump can be seen. The cement dosage of mixtures was 300 kg. The slump values of mixtures which contain no admixture are not same. When treated water was used the increase in slump was 1 cm. No effect could be seen in slump of concrete mixtures with VC and LS type of admixtures. There is a slight increase for the mixture produced with NS type of admixtures. Effect of magnetization of water was found negligible when the cement dosage was 300 kg. Another reason of this can be the higher slump values because of the cement dosage difference. As seen in Figure 5.7 the slump of mixes without treatment is higher than the mixes produced with 290 kg cement. Maybe the treatment is much effective for lower slump values.

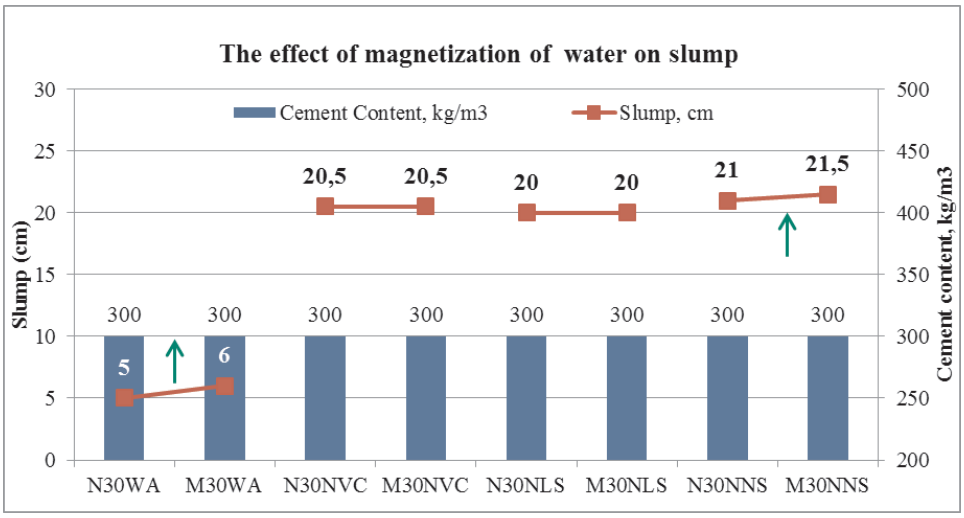

Figure 5.7. The effect of treated water on slump of concrete (300 kg cement dosage).

InFigure 5.8, the effect of magnetization of admixture on slump can be seen. The cement dosage of mixtures was 290 kg. The slump values increased for the mixtures produced with VC and NS type of admixtures when treated water was used. The increase in slump for mixtures is 2 cm and 3 cm, respectively. This increase is also impressive. The slump values of mixture with LS type of admixture were same when treated water was used. These results are in agreement with the results given in Figure 5.6.

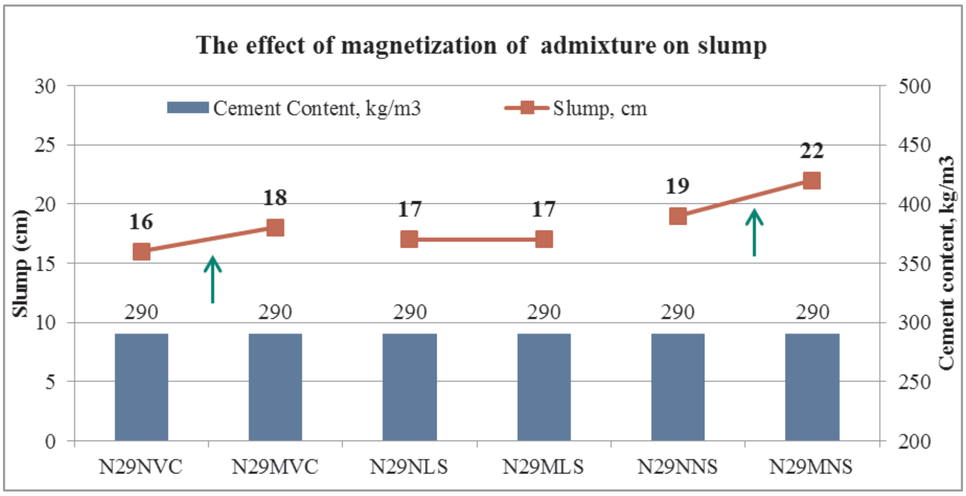

Figure 5.8. The effect of treated admixture on slump of concrete (290 kg cement dosage).

In Figure 5.9, the effect of magnetization of admixture on slump can be seen. The cement dosage of mixtures was 300 kg. No effect could be seen in slump of concrete mixtures with VC type of admixtures. There is a slight increase for the mixture produced with NS type of admixture and a slight decrease for the mixture produced with LS type of admixture. These results are also in agreement when the effect of magnetically treated water for 300 kg cement dosage was examined (Figure 5.7).

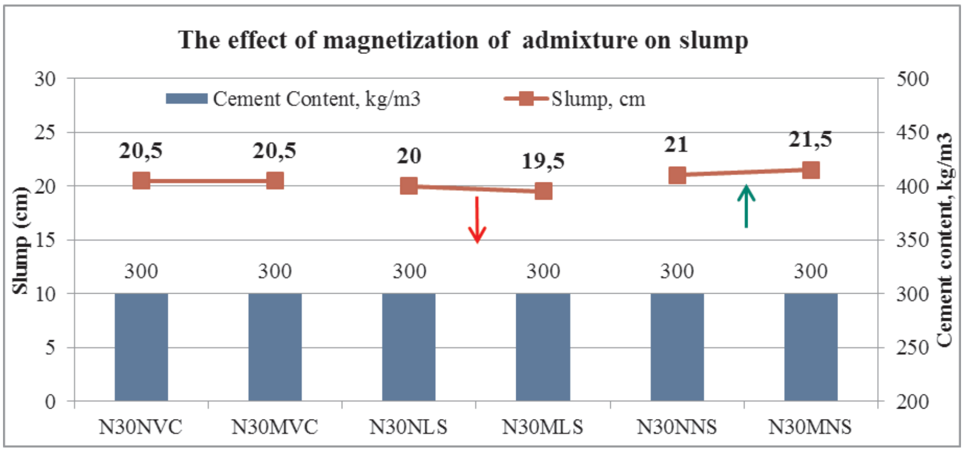

Figure 5.9. The effect of treated admixture on slump of concrete (300 kg cement dosage).

In Figure 5.10, the effect of magnetization of both water and admixture on slump can be seen. The cement dosage of mixtures was 290 kg. The slump values increased for the mixtures produced with VC and NS type of admixtures when treated water and admixture were used. The increase in slump for both mixtures is 2 cm and 2.5 cm, respectively. There is a slight decrease for the mixture produced with LS type of admixture.

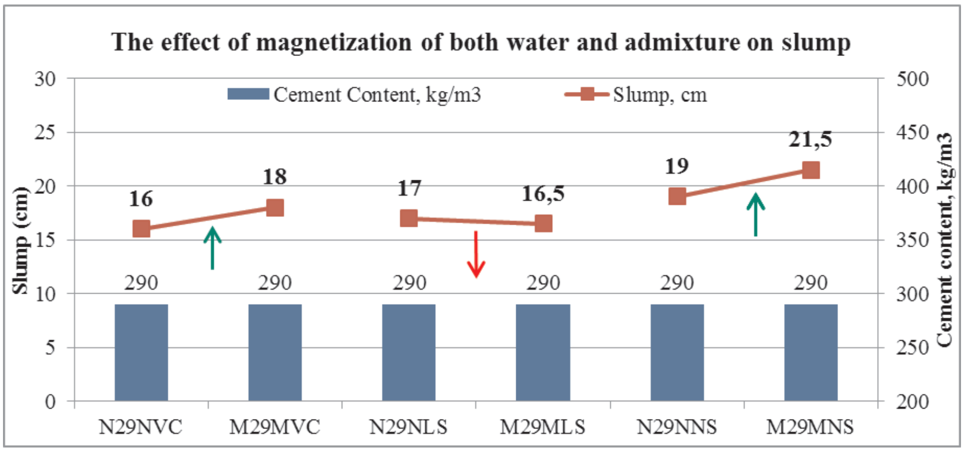

Figure 5.10. The effect of both treated water and admixture on slump of concrete (290 kg cement dosage).

In Figure 5.11, the effect of magnetization of both water and admixture on slump can be seen. The cement dosage of mixtures was 300 kg. The slump values increased for the mixtures produced with VC and NS type of admixtures when treated water was used. The increase in slump for both mixtures is 1 cm. There is a slight decrease for the mixture produced with LS type of admixture.

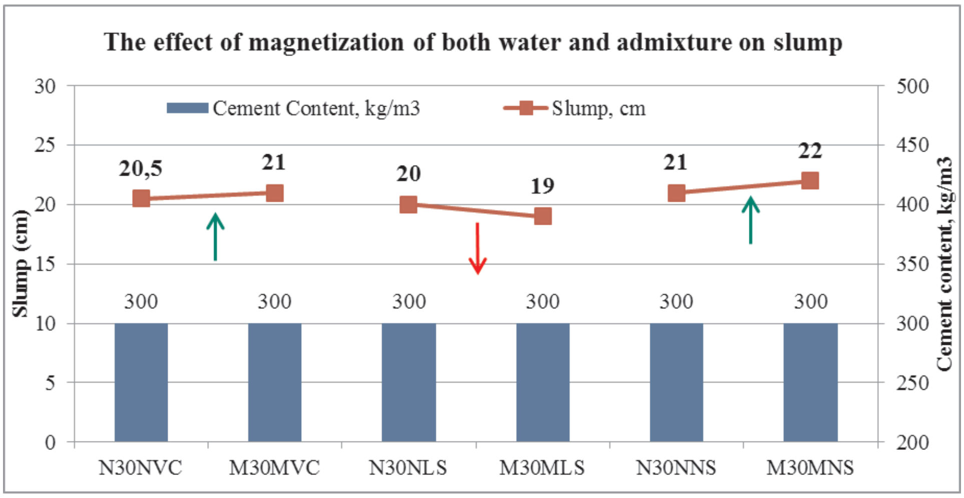

Figure 5.11. The effect of both treated water and admixture on slump of concrete (300 kg cement dosage).

As a result when magnetically treated water or admixture is used in concrete production, there can be an improvement in slump especially. But there may be an incompatibility between treated water and type of admixture. In this study, 3 types of admixtures were used. And treated water seems to have an effect on two of the admixtures which are VC and NS. The slump values were same or lower when treated water or admixture was used at mixes with LS type of admixtures. It can be said that the type of admixture and cement dosage are important parameters. Increasing the cement dosage leads to an increase in slump. So maybe the reason of negligible effect on the mixes with a cement dosage of 300 kg is their higher slump values. This should be considered valid for the materials in this study.

Another study was about the retention of slump. It was decided to use NS type of admixtures because this admixture worked better for both mixtures produced by using 290 kg and 300 kg cement. After production of concrete, the slump of mixtures was measured. Then the mixtures were kept in a container for an hour and the slump was measured again. Slump retention is very important because in industrial production the slump of concrete at site is more important than the initial slump. At site to increase the workability of water re-dosing admixtures are used. This means extra cost.

As seen in Figure 5.12, the initial and final slump values of mixtures are shown. For this study, the mixtures produced with 300 kg cement and NS type of admixture was used.

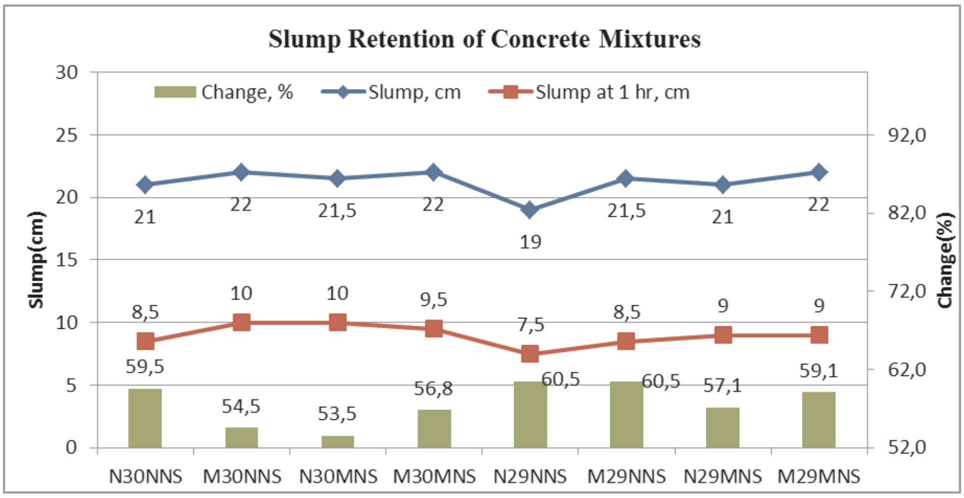

Figure 5.12. Slump retention of concrete mixtures.

According to changes between initial and final slump values shown in Figure 5.12, it can be said that for mixtures with 300 kg cement dosage the slump loss slightly decreased when the water or admixture was treated. However, this is a very small change. The error of the test should be considered. According to Gage R and R analysis the standard deviation of slump measurement is nearly 0.5 cm.

As a result the treatment of water or admixtures does not seem to affect the slump loss in a significant amount. The reasons of this situation can be the memory of water .This means the magnetic treatment on water can lose its effect by the time. It was reported that the persistence of magnetization on water can continue for several hours or even days. Wang *et al.*, [64] reported that the magnetization can achieve the best effect on water within 2 hours.

5.3. Mechanical Properties of Concrete

Compressive strength of all mixtures is shown in Table 5.7. Concrete mixtures produced with VC, NS and LS type of admixtures and no admixture have constant water/cement ratio. According to the compressive strength and slump values it was decided to produce concrete mixtures at same slump value with VC type of admixture. Also another experiment was designed to investigate the treatment effect on flowability. Two mixtures were produced at same flow range. These mixtures did not have same water/cement ratio because of the effect of water treatment.

In Table 5.7 the changes in 28-day compressive strength of each mixture with same cement dosage and admixture type are also given. R means reference.

Table 5.7. Compressive strength of concrete mixtures.

	Code	Compressive Strength (7 days) (MPa)	Compressive Strength (28 days) (MPa)	Change in 28 -day strength (%)	Slump (cm)
1	N29WA	33.2	42.1	R	4
2	M29WA	34	43.2	**2.6**	4
3	N30WA	35.7	44.3	R	5
4	M30WA	35.3	45.9	**3.6**	6
5	N29NVC	35.1	42.3	R	16
6	M29NVC	35.5	44	**4.0**	18.5
7	N29MVC	36.2	44.6	**5.4**	18
8	M29MVC	36.6	45.1	**6.6**	18
9	N30NVC	37.2	46.3	R	20.5
10	M30NVC	38	46.9	**1.3**	20.5
11	N30MVC	37.3	47.4	**2.4**	20.5
12	M30MVC	37.1	45.3	-2.2	21
13	N29NLS	36.2	45.1	R	17
14	M29NLS	38.1	46.6	**3.3**	16
15	N29MLS	38	44.6	-1.1	17
16	M29MLS	37.4	46.3	**2.7**	16.5
17	N30NLS	38.1	46.4	R	20
18	M30NLS	37.6	46.2	-0.4	20
19	N30MLS	37.8	47.8	**3.0**	19.5
20	M30MLS	39	47.7	**2.8**	19
21	N29NNS	39.2	48	R	19
22	M29NNS	38.7	47.5	-1.0	21.5
23	N29MNS	38.9	49.5	**3.1**	22
24	M29MNS	38.6	48.9	**1.9**	21.5
25	N30NNS	41.1	50.6	R	21
26	M30NNS	40.2	50	-1.2	21.5
27	N30MNS	40.1	51.2	**1.2**	21.5
28	M30MNS	40.7	49.7	-1.8	22
29	N30NVC2	39.8	47.7	R	20
30	M30NVC2	42.8	52.2	**9.4**	20
31	N44NP	70.3	85.2	R	50.75
32	M44NP	71.8	88.1	**3.4**	52

In Figure 5.13, it is clearly seen that there is an increase in 28-day compressive strength of the mixtures(290kg cement dosage) with treated water or admixture. The change is between 4% and 6.6%. The same situation is not valid for the mixtures with 300 kg cement dosage. Although there is an increase in 28-day compressive strength of mixtures with treated water and treated admixture, it is lower. For the mixtures produced with 290 kg cement the highest 28-day and 7-day compressive strength was seen at mixture M29MVC . For the mixtures produced with 300 kg cement the highest 28-day compressive strength was seen at mixture N30MVC and the highest 7-day compressive strength was seen at mixture M30NVC. It can be said when VC type of admixtures was used, an increase in compressive strength was achieved.

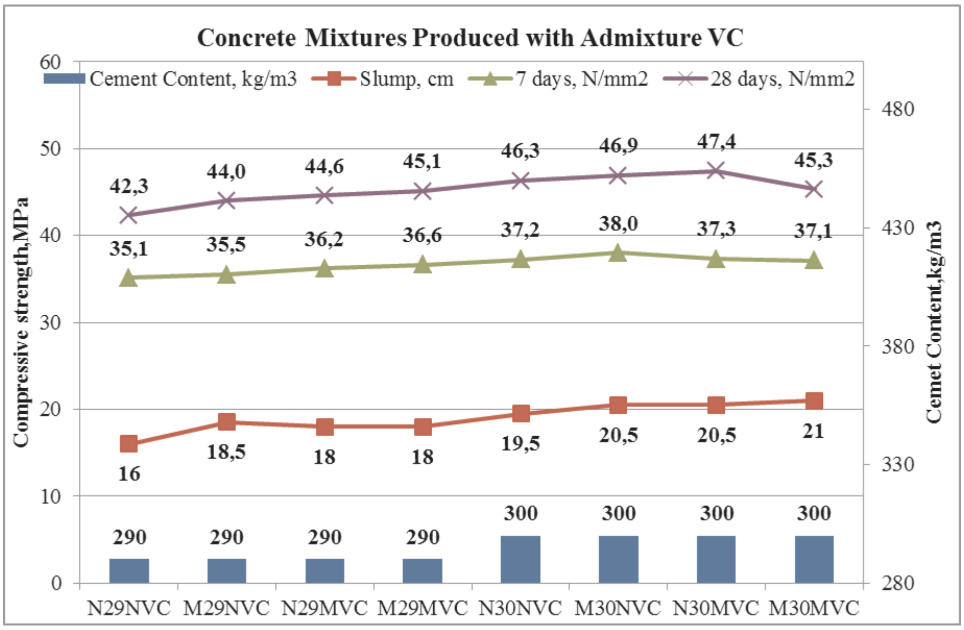

Figure 5.13. Compressive strength of concrete mixtures produced with VC type of admixtures.

In Figure 5.14 shows the compressive strength values for the mixtures produced using LS type of admixture. The highest 28-day compressive strength values was seen for the mixtures coded as N30MLS and M30MLS. The change in strength is 5% and 2.8%, respectively. For the mixtures produced with 290 kg cement, the highest 28-day and 7-day compressive strength was seen at mixture M29NLS.

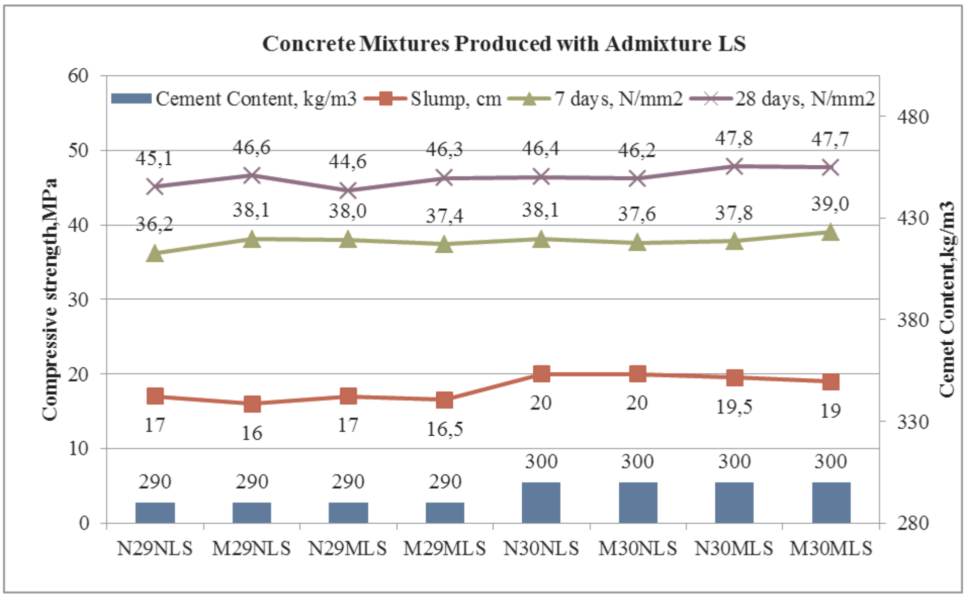

Figure 5.14. Compressive strength of concrete mixtures produced with LS type of admixtures.

In Figure 5.15, 28-day compressive strength of mixtures with 300 kg cement are close to each other. The highest change in 28-day compressive strength was seen for the mixture produced with treated water and 290 kg cement(M29NNS). The change is 3.1%.

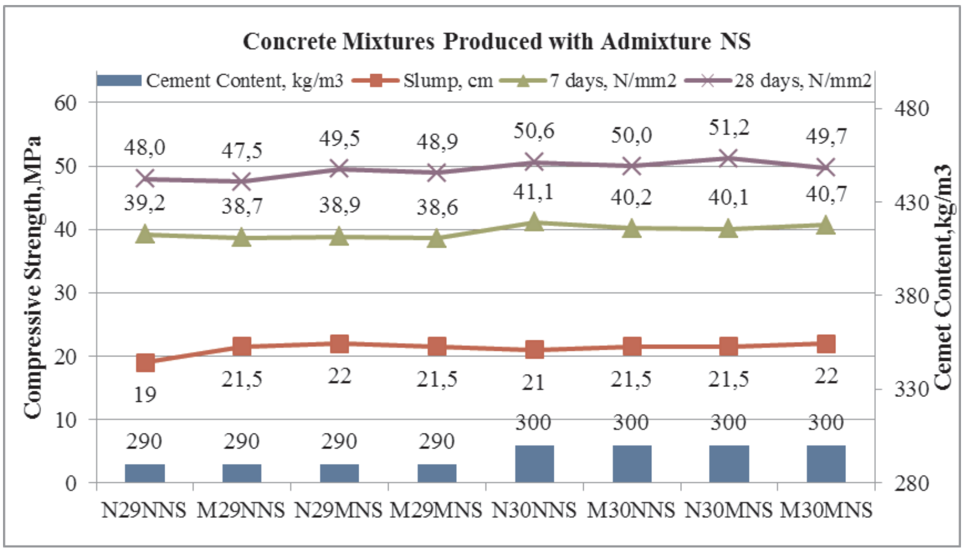

Figure 5.15. Compressive strength of concrete mixtures produced with NS type of admixtures.

Because of the improvement in workability of concrete it was decided to fix the slump value and test the compressive strength. It was aimed to see the change in compressive strength at same slump. VC type of admixtures was chosen to produce concrete mixtures because the highest change in compressive strength was obtained by using this admixture.

In Figure 5.16 it is seen that concrete mixtures at same slump produced with treated water gave higher compressive strength values. 7-day average compressive strength of mixture produced with normal water was 39.8 MPa whereas it was 42.8 MPa for treated water. 28-day average strength of concrete produced with normal water was 47.7 MPa whereas it was 52.2 for treated water. All the mixtures have a same slump value of 20 cm and only the water/cement ratios were different because by using magnetically treated water less water was needed to get the same slump.

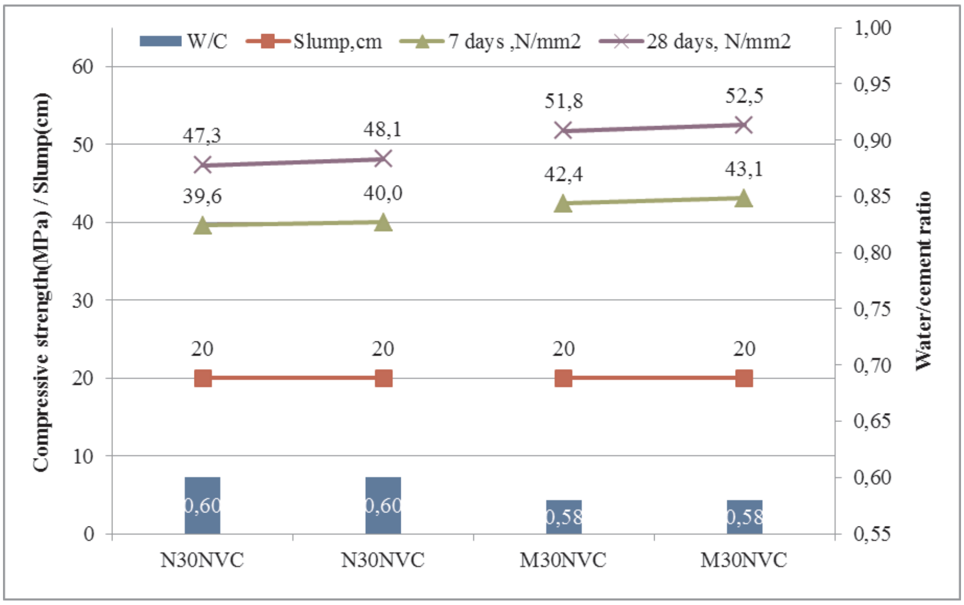

Figure 5.16. Compressive strength of concrete mixtures produced with VC type of admixtures(different w/c ratios).

The effect of treated water on concrete compressive strength was also investigated for self-compacting concrete. As shown in Figure 5.17, 7-day and 28-day compressive strength of concrete produced with normal water was 70.3 MPa and 85.2 MPa. These values were 71.8MPa and 88.1 MPa for concrete produced with treated water. The flowability of mixtures was nearly same. Adjusting the flowability is not as easy as in slump test. But the difference between the flow diameters is acceptable.

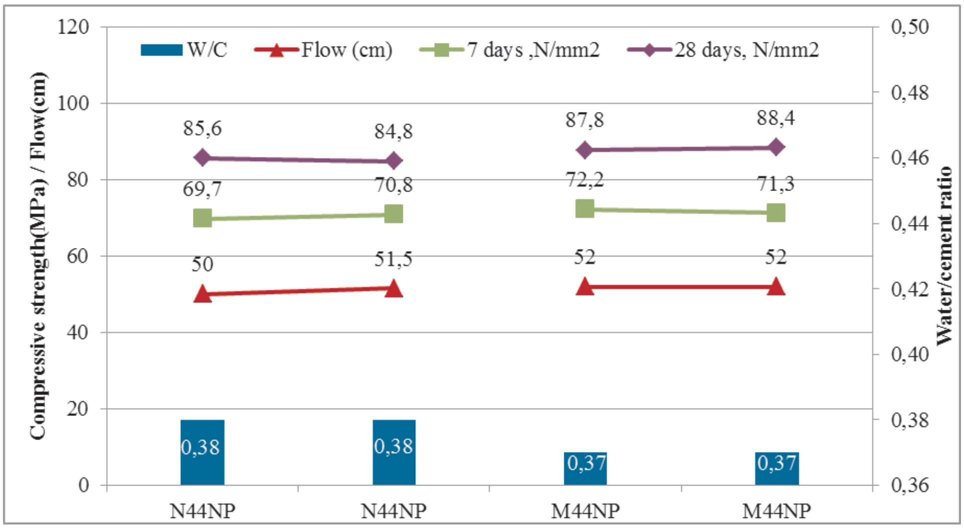

Figure 5.17. Compressive strength of concrete mixtures produced with P type of admixtures.

Based on the results obtained in this study it can be said that magnetic treatment of water has an effect on compressive strength. If this result is evaluated based on the findings in literature following explanations may be given.

(i) As it was given before, most studies given in literature and the tests carried out in the scope of this study show that the size of clusters in water decreases when a magnetic field is applied[19, 20]. Some researchers [20] claim that decreased size of clusters makes water much more effective for hydration reaction and this may result in higher strength. As known, cement hydration starts up from the surface of cement grain [2] and by the time a dense layer composed of hydration products covers the cement grain surface. This dense layer can make water hard to diffuse into the unhydrated cement zone. But small water clusters can diffuse easier [20].

(ii) Second theory is that because of smaller clusters in magnetically treated water, the thickness of the water layer on the cement grain is thinner than normal water [19]. This can cause a reduction in water demand for hydration and w/c ratio decreases. This theory explains improvement of slump for some mixtures when magnetized water and/or admixture are used.

(iii) Third theory is about the surface tension of water. The surface tension of treated water was measured and it is lower than the surface tension of tap water. As shown in Figure 5.18, the decrease in surface tension can imrove hydrophilic property. Water with low surface tension can wet the cement grains better. Some superplasticizers include surfactants to decrease the surface tension of water[70, 71]. In this regard, magnetically treated water can have similar effects as water reducing admixtures. Probably this is the main reason for the improvement in concrete workability.

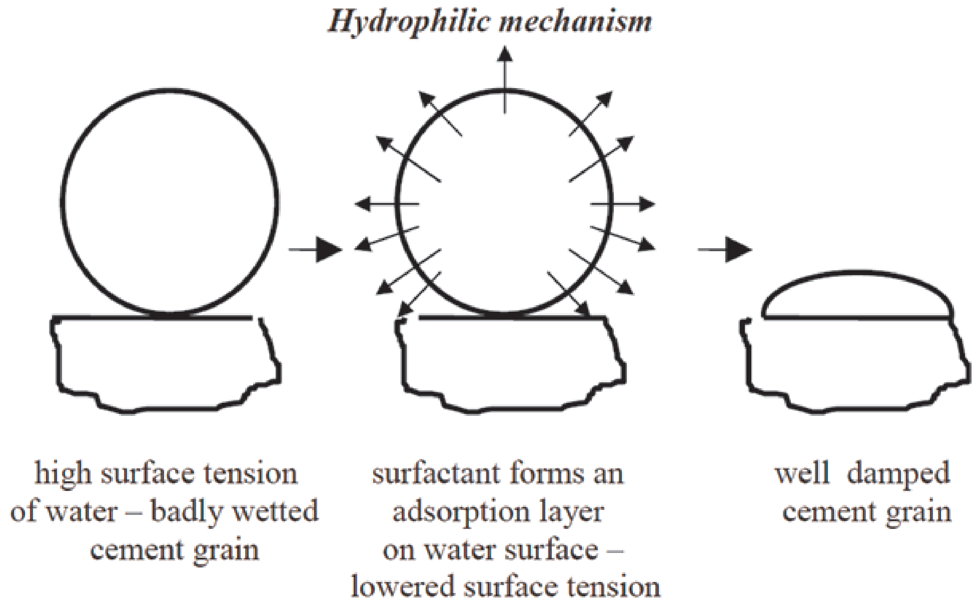

Figure 5.18. The effect of water surface tension on cement wetting.

In this study, increase in slump and compressive strength were found correlated which may be explained as increase in slump may be the reason for increased compression strength.

All theories may be acceptable and following conclusion may be drawn. The change in water properties due to applied magnetic field results in improved slump and compressive strength for some of the mixtures. However, this effect on slump and compressive strength is not as significant as the effects found in literature. The reason for this is considered to be based on the differences in the used materials, equipment and experimental methods.

To examine and compare the results of this study and other studies in literature, Table 5.8 was prepared. In Table 5.8, compressive strength values of some studies about the effects of treated water on concrete properties can be found. When the table is examined, it will be seen that treatment of water affects the compressive strength of concrete. The increase in compressive strength of concrete that were found by the researchers is higher than the results of this study. They also found that effect of treatment is influenced by magnetic field intensity and treatment time.

Ahmed *et al.*, [21] found improvements in slump and compressive strength of concrete. The slump of concrete was too low for workability. They focused on 7 - day compressive strength. The increase in 7-day compressive strength when magnetically treated water was used was above 10%. According to his study, the treatment time and the flow velocity can change the effect of treatment on water and concrete. No admixture was used in their study.

Su *et al.*, [10] fixed the treatment time and used different intensity of magnetic field. According to their study, the highest compressive strength was measured when the intensity of magnetic field was 0.8 T. The increase in compressive strength was nearly 25%. They found that the increase in intensity of magnetic field does not always make the treatment efficiency. No admixture was used in their study.

Abdel-Raouf *et al.*, [15] found that the magnetically treated water can enhance. the slump of all the mixtures produced with treated water was higher than the reference one. They found contradictory results in compressive strength. The best result was found at M25 compared to N2.

Table 5.8. Some studies in literature about effects of treated water on compressive strength and consistency of concrete (N= Tap water , M= Magnetically treated water).

Specimen	Treatment time (s/l)	Velocity of flow (m/s)	Magnetic field strength (T)	Cement content (kg)	W/C	Super-plasticizer type and ratio (%)	Slump /Flow (cm)	7-day average compressive strength (MPa)	28-day average compressive strength (MPa)
Ahmed [21]									
N	-	-	-	400	0.45	0	2.0	27.10	47.3
M1	2.5	1.27	1.2	400	0.45	0	5.5	32.50	-
M2	4.5	0.71	1.2	400	0.45	0	6.5	32.80	53.4
M3	7.5	0.42	1.2	400	0.45	0	5.0	32.50	-
M4	10.0	0.32	1.2	400	0.45	0	4.5	31.00	-
M5	12.5	0.25	1.2	400	0.45	0	4.0	30.25	-
M6	15.0	0.20	1.2	400	0.45	0	4.0	30.00	-
Su [10]									
N	2.7	-	0	357	0.51	0	-	-	29.6
M1	2.7	-	0.2	357	0.51	0	-	-	34.5
M2	2.7	-	0.4	357	0.51	0	-	-	33.2
M3	2.7	-	0.6	357	0.51	0	-	-	34.2
M4	2.7	-	0.8	357	0.51	0	-	-	36.9
M5	2.7	-	1.2	357	0.51	0	-	-	32.9
M6	2.7	-	1.35	357	0.51	0	-	-	31.4
Abdel-Raouf [15]									
N1	-	-	0	400	0.45	-	15	23.3	32.4
M11	-	-	0.1	400	0.45	-	18	22.0	27.7
M12	-	-	0.2	400	0.45	-	15	22.9	29.7
M13	-	-	0.3	400	0.45	-	17	21.7	31.6
M14	-	-	0.4	400	0.45	-	16	21.8	27.9
N2	-	-	0	450	0.35	-	6.5	39.5	43.7
M22	-	-	0.1	450	0.35	-	9.5	29.1	45.7
M23	-	-	0.2	450	0.35	-	12	33.5	42.8
M24	-	-	0.3	450	0.35	-	15	43.1	48.8
M25	-	-	0.4	450	0.35	-	21	36.6	51.1

5.4. Durability of Concrete

5.4.1. Rapid Chloride Permeability Test

The test was conducted at Boğaziçi University Construction Materials Laboratory. Rapid chloride permeability test (RCPT) was carried out for concrete mixtures produced with VC and NS types of admixtures and different cement contents. The current values measured are shown in Table 5.9 and the values of charges passing through the specimens are shown in Figure 5.14 and Figure 5.15.

Table 5.9. Rapid chloride permeability test results of concrete mixtures.

	Concrete Mixtures							
Current (A)	N29NVC	M29NVC	N29MVC	M29MVC	N30NNS	M30NNS	N30MNS	M30MNS
I_0	0.19	0.183	0.194	0.188	0.205	0.196	0.185	0.207
I_{30}	0.203	0.197	0.206	0.195	0.218	0.2	0.197	0.208
I_{60}	0.207	0.203	0.211	0.197	0.224	0.202	0.211	0.216
I_{90}	0.21	0.207	0.212	0.203	0.229	0.21	0.222	0.219
I_{120}	0.237	0.23	0.242	0.228	0.232	0.216	0.23	0.223
I_{150}	0.25	0.239	0.251	0.237	0.246	0.223	0.236	0.229
I_{180}	0.258	0.244	0.257	0.244	0.255	0.23	0.246	0.232
I_{210}	0.269	0.25	0.27	0.253	0.258	0.232	0.248	0.236
I_{240}	0.274	0.256	0.275	0.256	0.258	0.235	0.252	0.235
I_{270}	0.28	0.262	0.28	0.262	0.259	0.237	0.254	0.236
I_{300}	0.288	0.263	0.287	0.268	0.261	0.24	0.259	0.237
I_{330}	0.292	0.265	0.287	0.271	0.261	0.241	0.26	0.237
I_{360}	0.293	0.267	0.29	0.273	0.262	0.241	0.262	0.24
Q(coulomb)	5417.1	5113.8	5436	5120.1	5279.5	4832.1	5109.69	4917.06

As seen in Table 5.9, the lower values were seen at the mixtures produced with treated water. The test results are higher for the concrete mixtures produced with treated admixture compared to treated water.

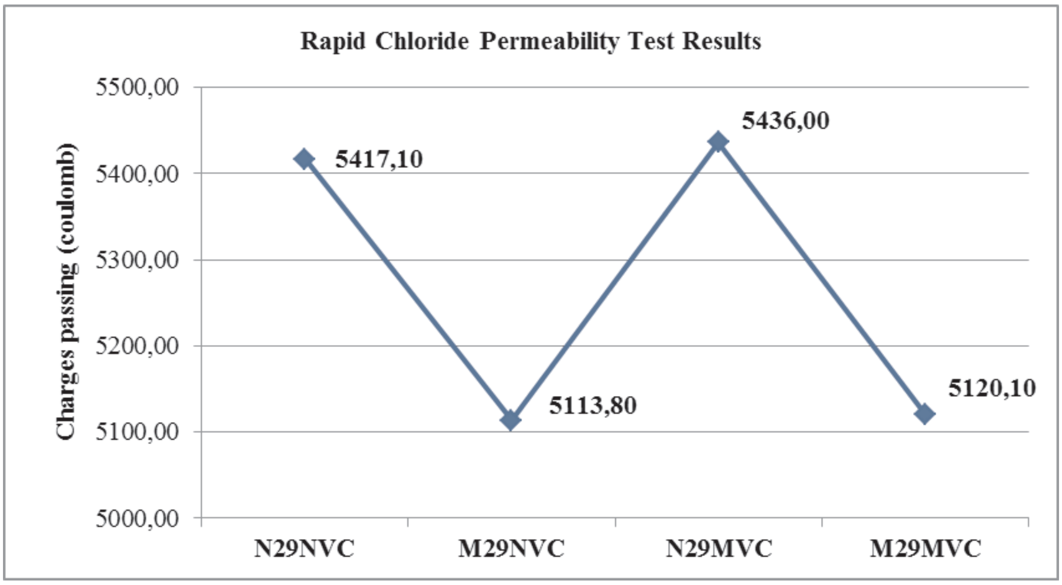

Figure 5.19. Rapid chloride permeability test results of concrete mixtures produced.

In Figure 5.19 it is seen that rapid chloride permeability of mixtures produced with treated water is lower. On the other hand, it is a bit higher for the mixture produced with treated admixture. Similarly as seen in Figure 5.20 the rapid chloride permeability of mixtures produced with treated water or admixture is lower.

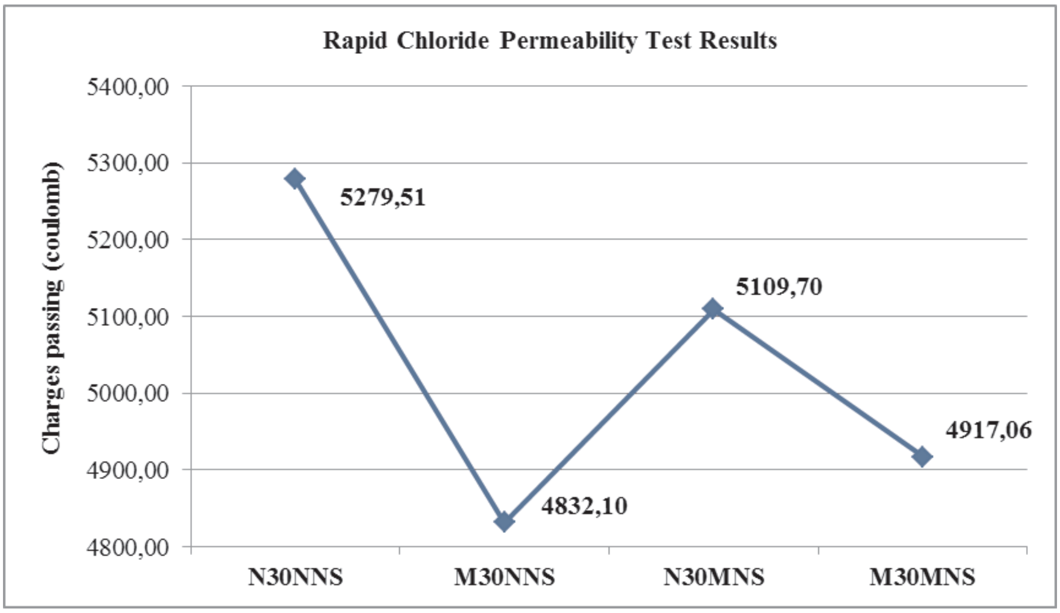

Figure 5.20. Rapid chloride permeability test results of concrete mixtures produced.

It is hard to interpret the results of rapid chloride permeability test. As seen in

Table 5.10 there is no correlation between compressive strength and the results of the test.

Table 5.10. Compressive strength of samples used for RCPT.

Code	**Compressive Strength (28 days)(MPa)**	Q(coulomb)
N29NVC	42.3	5417.1
M29NVC	44	5113.8
N29MVC	44.6	5436
M29MVC	45.1	5120.1
N30NNS	50.6	5279.5
M30NNS	50	4832.1
N30MNS	51.2	5109.69
M30MNS	49.7	4917.06

5.4.2. Water Penetration Test under Pressure

The test was done at Akcansa Cement Laboratory. Water penetration test under pressure was carried out for concrete mixtures produced with VC and NS types of admixtures.

As seen in Figure 5.21 the penetration of water of the concrete without any treatment is 0.7 cm. When treated water was used it is 0.4 cm. But when treated admixture was used the penetration is 1.1 cm.

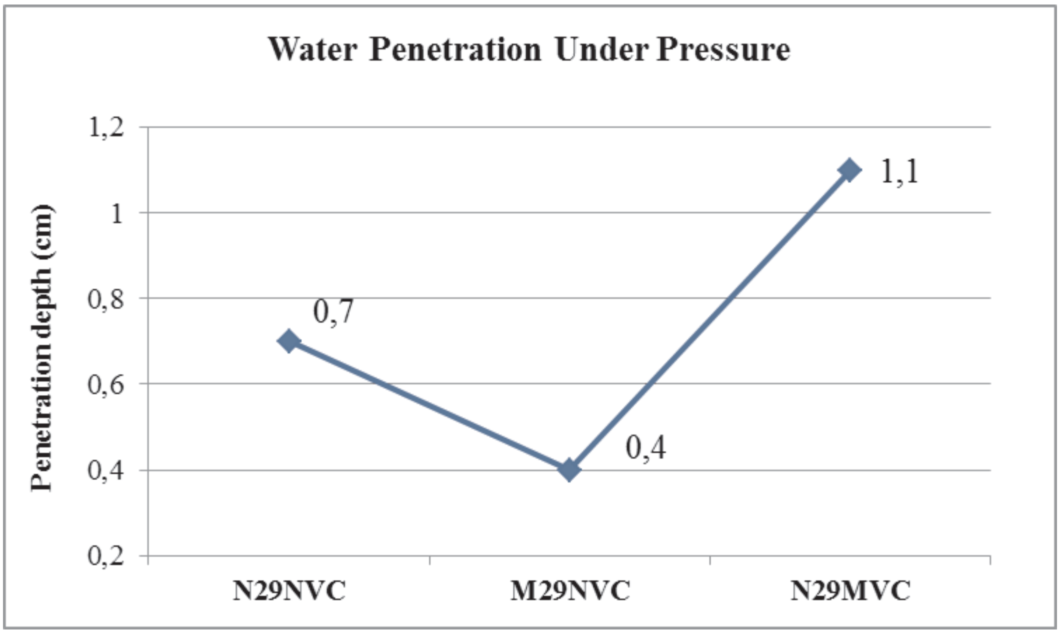

Figure 5.21. Penetration of water for mixtures produced with VC type of admixture.

As seen in Figure 5.22 the penetration of water of the concrete without any treatment is 1.8 cm. When treated water was used it is 0.9 cm and when treated admixture was used the penetration is 1.1 cm. These values are smaller and better.

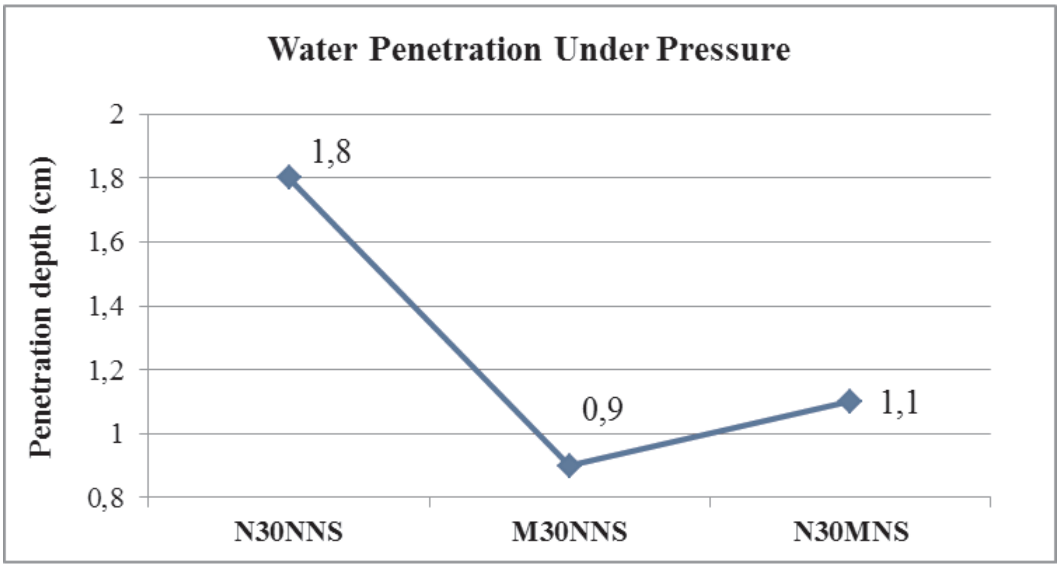

Figure 5.22. Penetration of water for mixtures produced with NS type of admixture.

The water/cement ratio of all the mixtures was same. It is know that water/cement ratio is the basic parameter for permeability of concrete. So the reason of low penetration of mixtures produced with magnetically treated water can be the effect of treated water. Same situation was not seen for treated admixture.

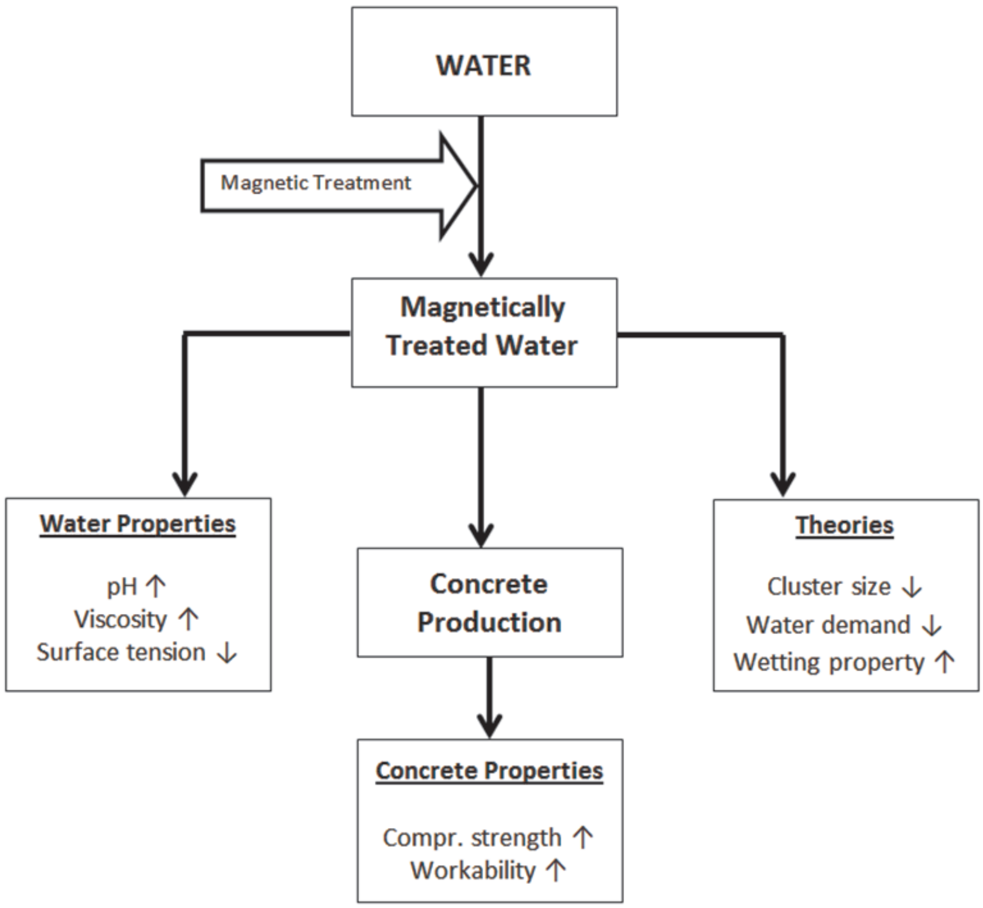

Figure 5.23. The summary of the process of the study and results.

6. CONCLUSIONS

The main objective of this study was to investigate the effect of magnetic treatment of water on concrete properties. Also the effect of magnetic treatment of concrete chemical admixtures was investigated, because admixtures used in concrete production consist of water and solid matter. To understand the effects of magnetic treatment of water on concrete properties some investigations on water such as surface tension, pH, viscosity, FTIR and NMR analysis were also conducted. Although there are not enough studies in literature, it was achieved to obtain enough studies in various disciplines such as medicine, agriculture and physics.

The results of tests on water were very important and necessary to understand the effect of magnetization on water and what it leads to in properties of concrete. 32 concrete mixtures were prepared with different type of admixtures and different amount of cement.

According to tests on water, it was found that there was a decrease in surface tension of water when it was exposed to magnetic field. On the other hand the viscosity and pH of water increased. NMR analysis showed that magnetic treatment can lead to a change in size of clusters in water. The decrease in size of clusters because of magnetization was may be one of the most important results in this study. Due to FTIR analysis it was found that magnetic treatment did not change the amount of compounds in water.

According to slump and slump retention test following results were drawn:

(i) There was an improvement in slump of concrete when magnetically treated water and/or admixture were used.

(ii) The type of admixture could change the effect of magnetically treated water on workability of concrete. It was not seen an improvement in slump of concrete with one of the admixture type.

(iii) There was no significant improvement in slump loss.

When magnetically treated water and/or admixture were used, increases in 28-day compressive strength were seen on some mixtures. It is hard to say magnetically treated water could absolutely increase the compressive strength. The method and equipment used in producing magnetically treated water are important parameters which influence the effect of magnetization. But the improvement in workability can enhance the compressive strength of concrete. When the slump of the mixtures produced with tap water and treated water was same, it was found that there was a clear increase in compressive strength of concrete because of decrease in water/cement ratio.

The results of rapid chloride permeability test and water penetration under pressure were confusing. The mixtures produced with treated water gave a better permeability performance rather than the mixtures produced with tap water or treated admixture. However, the low reproducibility and the variations in measuring complicates to draw a statement.

(i) The decrease in size of water clusters can improve the hydration reaction. Smaller molecules can diffuse inside the unhydrated cement grain much easier.

(ii) The decrease in size of water clusters can reduce the water demand for hydration. Because the thickness of the water layer on cement grain can be thinner.

(iii) Because of the decrease in surface tension of water the wetting property of water improves. So there can be an improvement in workability of concrete.

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