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Effect of magnetic water on the engineering properties of concrete containing granulated blast-furnace slag

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Abstract

This research investigates the compressive strength and workability of mortar and concrete, which were mixed with magnetic water and contained granulated blast-furnace slag (GBFS). The test variables included the magnetic strength of water, the content of GBFS in place of cement, and the water-to-binder ratio (W/B). Results show that the compressive strength of mortar samples mixed with magnetic water of 0.8–1.35 T increased 9–19% more than those mixed with tap water. Similarly, the compressive strength of concrete prepared with magnetic water increased 10–23% more than that of the tap water samples. In particular, the best increase in compressive strength of concrete is achieved when the magnetic strength of water is of 0.8 and 1.2 T. It is also found that magnetic water improved the fluidity of mortar, the slump, and the degree of hydration of concrete.

Keywords: Compressive strength; Workability; Concrete; Granulated blast-furnace slag; Magnetic water

1. Introduction

Water content in traditional concrete has a significant influence on its engineering properties such as mechanical strength. However, studies on water for concrete mixing have been scarce. When water flows through a magnetic field at a constant speed, it becomes magnetized and is known as magnetic water. Magnetization increases negative ionic hydration, thus intensifying the damaging effect on the water crystal structure [1]. With respect to concrete mixing, magnetization leads to reduced adsorption of active surface substances at the interface between water and cement. This in turn affects the hydration process and the hardening of cement. In the mixing of water and cement, hydration reaction will first take place on the surface of the cement particles. A thin layer of hydration products is thus formed on the cement particles, which hinders further hydration of the cement particles, thus preventing the development of mechanical strength of the concrete. However, if magnetic water is used instead, water molecules can easily penetrate into the cement particles, allowing a more complete hydration process to occur and enhancing the mechanical strength of concrete [2].

Researches in industrialized countries such as Russia and Mainland China have shown that using magnetic water for concrete mixing can increase its workability, accelerate the hydration reaction, increase its compressive strength, and improve its impermeability and freeze–thaw resistance. On the other hand, using appropriate quantity of granulated blast-furnace slag (GBFS) in place of cement can improve the concrete structure, making it denser and reducing the occurrence of dry shrinkage [3].

Besides the increase in compressive strength, there are also other advantages of preparing concrete with magnetic water. First, it reduces the amount of cement used. Moreover, it does not require the addition of chemical admixture, thus avoiding environmental pollution. The mixing process involves passing the water through the magnetic field, followed by the addition of coarse and fine aggregates, cement, and GBFS. The operation is

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Table 1
Physical properties of coarse and fine aggregates

Properties	Type	
	Coarse aggregate	Fine aggregate
Sp. gr	2.61	2.62
Absorptivity (%)	0.92	1.24
Fine modulus	–	2.84

easy and has great potential for application in concrete pre-mixing plants and building construction [4].

2. Experimental design

This study investigates the workability and compressive strength of cement mortar, concrete and cement paste mixed with magnetic water at different water-to-binder ratios (W/B). Moreover, the degree of hydration is analyzed and the effect of magnetized water of different field strengths on the engineering properties of fresh concrete is examined.

2.1. Materials

The cement used is Portland cement Type I produced by Taiwan Cement Company. Indigenous fine and coarse aggregates are obtained from Tsuo-Shui River in Central Taiwan. Their physical properties and size gradation are shown in Tables 1 and 2, respectively. The standard sand for making the mortar samples is Ottawa sand with grading that meets the requirement of ASTM C788. The mixing water of quality shown in Table 3 is produced by the Taiwan Tap Water in Touliu. Magnetization is carried out by passing the water through a magnetic field at 1350 l/h. Water quenched GBFS is obtained from Chung-Lian, Taiwan. Its physical and chemical properties are listed in Table 4. In this study, GBFS is used to substitute cement in the mixing process.

2.2. The mixture proportioning of samples

2.2.1. Concrete samples

Cement, GBFS, water, as well as coarse and fine aggregates are mixed according to the proportion listed in Table 5 to produce cylindrical concrete samples of radius 10 cm and height 20 cm. Test for compressive strength is performed after the concrete has been cured for 7, 28, and 56 days.

Table 2
Size gradation of coarse and fine aggregates

Coarse aggregate			Fine aggregate		
Sieve size (in.)	Pass (%)	ASTM C136 regulation (%)	Sieve size	Pass (%)	ASTM C136 regulation (%)
1	99.9	100–90	#4	99.5	100–95
3/4	92.7	–	#8	85.8	100–80
1/2	46.0	60–25	#16	59.6	85–50
3/8	26.4	–	#30	40.6	60–25
#4	0.8	10–0	#50	19.7	30–10
			#100	9.8	10–2

Table 3
The quality test of mixed water

Test item	Result	Regulatory standard for tap water
pH value	6.69	5–9
SO_4 salt (ppm)	125	<3000
Turbidity	0.05	<4
Residue after evaporation (g/l)	2.4	<30
$KMnO_4$ consumed (mg/l)	~ 0	<10
Suspended solid (g/l)	~ 0	<2
Dissolved solid (g/l)	~ 0	<2
Cl^- (ppm)	10.46	<200

2.2.2. Mortar samples

Cubic samples of 5 cm are made by mixing binder materials (cement and GBFS) and standard sand at a weight ratio of 1:2.75 according to ASTM C109. The mixture proportioning at W/B ratios of 0.4, 0.485, and 0.55 is shown in Table 6. Same as the concrete samples, the mortar samples undergo the test of compressive strength after they have been cured for 7, 28, and 56 days.

2.2.3. Cement paste samples

Cement paste is made by mixing cement, GBFS, and water on the basis of the mixture proportioning shown in Table 7. The weight ratio of water to binder is 0.29:1. According to ASTM C109, 5 cm cubes are prepared and cured under water at 23°C for 7, 28, and 56 days before performing the test of compressive strength and analyzing the degree of hydration.

Table 4
Physical and chemical properties of GBFS

Test item	Test result	Reference standard
Physical properties		
Fineness (cm^2/g)	407.4	>330
After #325 sieving	9.0	<20
Sp. gr	2.91	–
Chemical properties		
Air content of paste (%)	3.48	<12
Activity, 3 days (%)	72.3	–
Loss of ignition (%)	0.4	–
SiO_2 (%)	34.73	–
Al_2O_3 (%)	13.67	–
Fe_2O_3 (%)	0.31	–
CaO (%)	40.3	–
MgO (%)	7.46	<4
SO_3 (%)	1.19	>1.4
Alkalinity	1.77	<2.5
Sulfide sulfur	0.52	–
K_2O (%)	0.28	–
Na_2O (%)	0.08	–

Table 5
Mixture proportioning of concrete samples (W/B = 0.51), unit: kg/m^3

	Cement substitution by GBFS			
Materials	0%	5%	15%	25%
Cement	357	339	303	268
GBFS	0	18	54	89
Mixed water	182	182	182	182
Coarse aggregate	100	1008	1008	1008
Fine aggregate	827	827	827	827

2.3. Experimental variables

2.3.1. Magnetic field strength

Tap water is magnetized by flowing through the magnetic field of 0.2, 0.4, 0.6, 0.8, 1.2, and 1.35 T while 0 T denotes plain tap water.

2.3.2. Amount of cement substituted

The percentage of cement substituted by GBFS includes 5%, 15%, and 25% while 0% indicates no substitution. The substitution ratio is calculated according to the weight.

2.3.3. Water-to-binder ratio

The W/B ratio of concrete is 0.51, while that of mortar samples include 0.4, 0.485, and 0.55. The W/B ratio of cement paste is 0.29.

2.3.4. Age

All samples are cured under water at 23 ± 1°C for 7, 28, and 56 days before the tests are performed.

2.4. Experimental procedures

2.4.1. Compressive strength

The ELE 200-ton compressive test machine is used to test concrete and mortar samples according to ASTM C31 and C109, respectively.

Table 6
Mixture proportioning of mortar samples

	Cement substitution by GBFS				
Materials (g)	0%	5%	15%	25%	W/B
Cement	723	687	615	542	0.4
GBFS	0	36	108	181	
Mixed water	289	289	289	289	
Standard sand	1989	1989	1989	1989	
Cement	708	672.6	601.8	531	0.485
GBFS	0	35.4	106.2	177	
Mixed water	343.4	343.4	343.4	343.4	
Standard sand	1947	1947	1947	1947	
Cement	914.6	869	777.4	686.0	0.55
GBFS	0	45.7	137.2	228.6	
Mixed water	504	504	504	504	
Standard sand	2514.8	2514.8	2514.8	2514.8	

Table 7
Mixture proportioning of cement pastes

	Cement substitution by GBFS			
Materials (g)	0%	5%	15%	25%
Cement	500	475	425	375
GBFS	0	25	75	125
Mixed water	146	146	146	146

2.4.2. Slump

Fresh concrete undergoes the slump test according to ASTM C143.

2.4.3. Fluidity

The fluidity of fresh mortar samples with W/B ratios of 0.4, 0.485, and 0.55 are measured according to ASTM C230.

2.4.4. Degree of hydration

The weight loss of cement paste samples hydrated at 440°C, 580°C, and 1007°C are measured to determine the degree of hydration.

3. Results and discussion

3.1. Mortar samples

3.1.1. Effect of magnetic field strength

Fig. 1 shows the results of compressive strength test of mortar samples cured for 7, 28, and 56 days. Although the samples are of different W/B ratios and percentages of GBFS substitution, they all exhibit a similar trend, indicating that the effect of magnetic field strength of water on the compressive strength of different mortar samples is almost the same. As can be seen, the compressive strength of samples mixed with magnetic water is higher than that of the control (tap water represented by 0 T). In other words, magnetic water is more active than tap water during the hydration process. Therefore, we can conclude that whether there is GBFS substitution and whatever the GBFS content, the use of magnetic water can improve the compressive strength of mortar and the most significant increase can be observed when the magnetic water is 1.35 T.

3.1.2. Effect of age

As can be seen in Fig. 2, the effect of age on the compressive strength of mortar samples prepared with tap water and magnetic water shows great similarity. An increase in compressive strength can be observed when curing age becomes longer. Samples whose W/B = 0.4 with GBFS of 0%, 5%, 15%, and 25% all show the same trend of increase. In other words, a consistent pattern of increase in strength can be found in samples mixed with tap water and magnetic water as well as samples of different GBFS content.

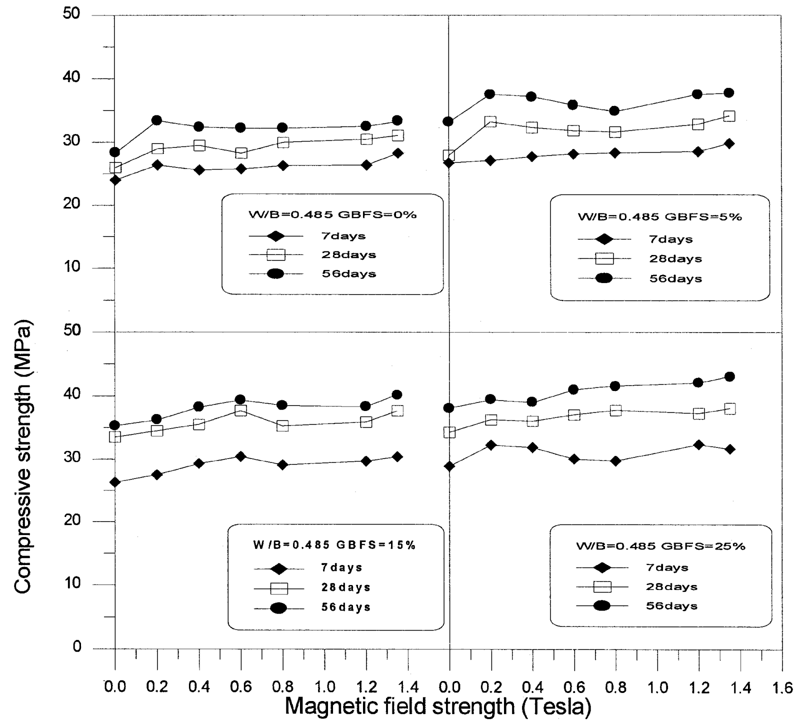

Fig. 1. Effect of magnetic water on compressive strength of mortar (W/B = 0.485).

3.1.3. *Effect of GBFS substitution*

Fig. 3 shows the changes in the compressive strength of mortar samples as a result of different quantities of GBFS substitution. Regardless of the W/B value, the samples containing GBFS of whatever percentage all show a greater compressive strength than those without

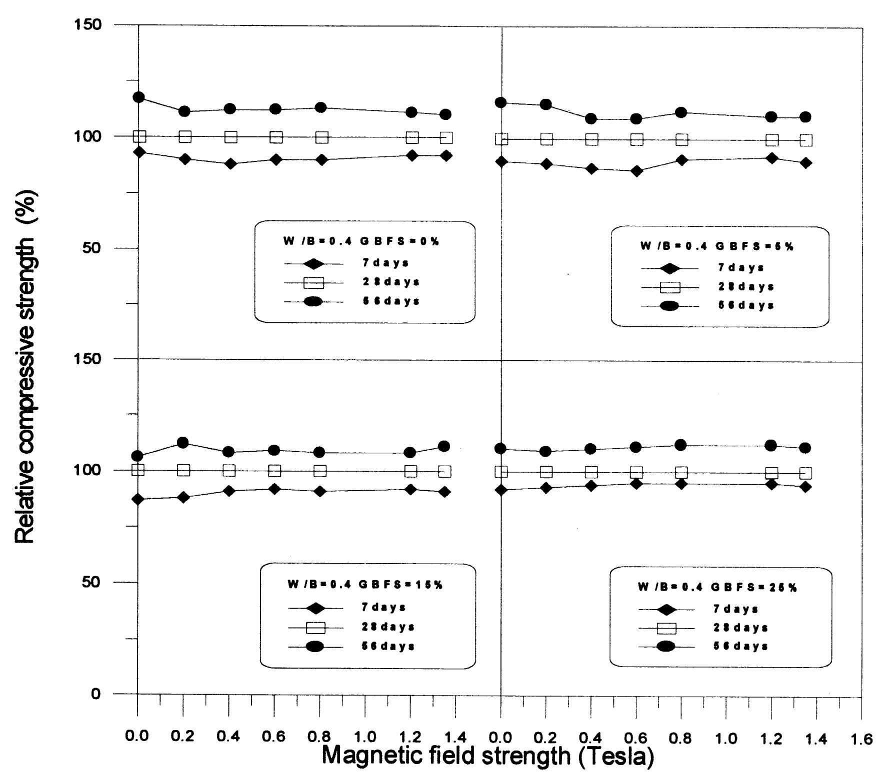

Fig. 2. Effect of age on the compressive strength of mortar (W/B = 0.4).

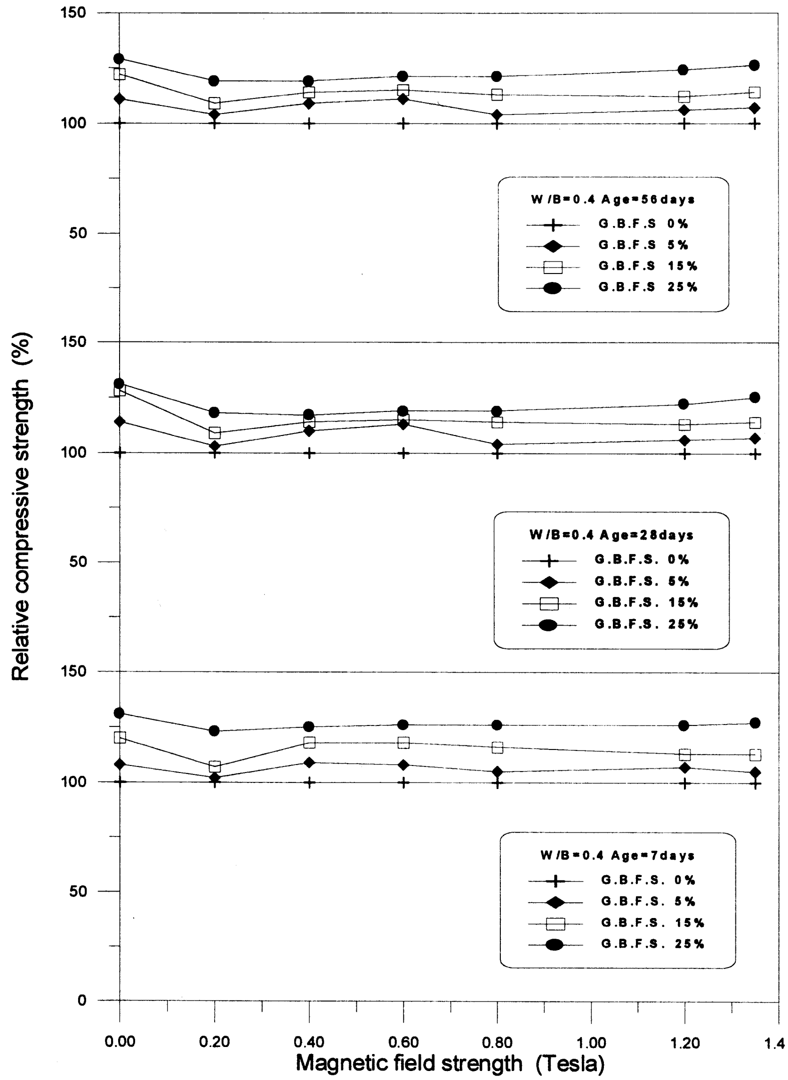

Fig. 3. Effect of GBFS on compressive strength of mortar (W/B = 0.4).

GBFS substitution. Therefore, we can conclude that the addition of GBFS helps to increase the compressive strength and such effect becomes more significant with longer curing age.

3.1.4. *Effect of W/B ratio*

An inverse relationship can be found between the W/B value and the compressive strength of mortar samples cured for 28 days, as shown in Table 8. Lower W/B ratio can improve compressive strength, which deteriorates at higher W/B ratio. The same phenomenon can be found for samples cured for 7 and 56 days; while samples prepared with tap water and magnetic water all show the same trend of changes.

3.1.5. *Fluidity*

Magnetic strength has a positive effect on fluidity. As seen in Table 9, the fluidity of fresh mortar prepared with magnetic water is higher than that mixed with tap water. The

Table 8
Effect of W/B on compressive strength of mortar samples (28 days)

	Magnetic water						
W/B	0 T	0.2 T	0.4 T	0.6 T	0.8 T	1.2 T	1.35 T
0.4	+5%	+6%	+7.3%	+12.3%	+5.8%	+5.5%	+4.3%
0.485	100%	100%	100%	100%	100%	100%	100%
0.55	−8%	−10.5%	−10.3%	−10%	−6%	−4%	−4%

Table 9
Effect of magnetic water on fluidity of fresh mortar samples (unit: cm)

	Magnetic water						
Fluidity	0 T	0.2 T	0.4 T	0.6 T	0.8 T	1.2 T	1.35 T
Diameter (cm)	18	18.5	18.8	18.9	19.2	19.0	19.6
Relative value (%)	100	103	105	105	107	106	109

Table 10
Effect of magnetic water on compressive strength of concrete samples (unit: MPa)

		Magnetic water						
Cement substitution by GBFS	Age (days)	0 T	0.2 T	0.4 T	0.6 T	0.8 T	1.2 T	1.35 T
0%	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
5%	7	26.5	28.0	31.2	31.7	31.1	32.5	31.1
	28	29.6	30.5	34.8	35.7	35.4	36.9	35.1
	56	32.4	33.6	38.4	39.1	37.8	39.4	37.3
15%	7	26.0	29.0	31.4	28.5	32.6	33.7	29.6
	28	32.6	34.7	37.3	33.2	38.3	39.0	35.1
	56	36.9	39.4	42.3	38.9	42.1	42.1	39.2
25%	7	23.5	29.0	30.1	28.0	30.4	29.4	28.2
	28	29.6	35.3	38.0	34.7	36.3	35.8	34.7
	56	33.7	38.3	40.4	38.4	39.2	38.7	39.4
Relative compressive strength of four substitutions	7	100%	113%	119%	115%	123%	121%	114%
	28	100%	111%	118%	114%	121%	119%	113%
	56	100%	110%	116%	113%	117%	117%	111%

same phenomenon can be found in samples with GBFS substitution. In other words, the use of magnetic water and the addition of GBFS can increase the fluidity of fresh mortar. This also shows that magnetic water is effective in dispersing the GBFS.

3.2. Concrete samples

3.2.1. Effect of magnetic field strength

Table 10 shows the effect of the magnetic field strength of water on the compressive strength of concrete when W/B = 0.51. It can be seen that with the same GBFS content and same curing age, the compressive strength of concrete mixed with tap water is lower than that mixed with magnetic water of 0.2–1.35 T; and the greatest increase in compressive strength can be achieved using magnetic water of 0.8 and 1.2 T.

3.2.2. Effect of age

The effect of age on the compressive strength of concrete with W/B = 0.51 can be seen in Table 10. Concrete samples prepared with tap water and with magnetic water all show a similar trend of increase in compressive strength with longer curing age.

3.2.3. Effect of GBFS substitution

As seen in Table 10, there is no significant change in the compressive strength between concrete samples of 5% GBFS substitution and those without substitution at 7 days. However, the addition of 15% and 25% GBFS will slightly slow down the compressive strength for concrete at 7 days. With respect to samples cured for 28 days, concrete samples containing GBFS show a higher compressive strength than those at 0% substitution, the increase in strength for concrete with 5%, 15%, and 25%

Table 11
Degree of hydration of concrete samples (W/B = 0.485), unit: %

		Magnetic water						
Cement substitution by GBFS (%)	Age (days)	0 T	0.2 T	0.4 T	0.6 T	0.8 T	1.2 T	1.35 T
0	7	60.5	61.8	62.5	61.8	64	64	65.5
	28	64.2	65	66	66	67.7	67.4	69.7
	56	66	66.6	68	67.4	69.2	71.2	72.9
5	7	61.8	62.9	65.8	66	65.2	65.5	68.5
	28	68.2	69.4	72	72	72.6	73.6	74.8
	56	71.2	72.4	74.4	75.3	74.4	76	78
15	7	64.8	66.5	70.5	70.1	71.3	70.5	71.6
	28	73.4	73.2	75.3	76.3	74.8	75.7	78.2
	56	78.2	79.1	78.4	78	80	79.5	81
25	7	71.4	72.3	72	73	72	74.2	75
	28	75.5	76	76.4	77.3	76.2	79.1	79.8
	56	80.2	80.8	79.3	80	83.1	82	84.3

GBFS substitution are 2%, 8%, and 5%, respectively. As age was extended to 56 days, concrete samples with 15% and 25% GBFS substitution show an increase in compressive strength of 9% and 4%, respectively. Although at 7 days, concrete containing GBFS did not gain much strength, the increase became more significant at 28 and 56 days. This can be attributed to the pozzolanic reaction between the GBFS and the calcium-hydroxide, one of the cement hydration products, at long-term. In addition, it is also due to the relatively smaller GBFS size used here (fineness: 4074 cm^2/g) as compared with that of the cement particles (fineness: 3054 cm^2/g). Both at 28 and 56 days, the greatest increase in compressive strength is achieved at 15% GBFS substitution.

3.2.4. Degree of hydration

Table 11 shows that at 7, 28, and 56 days, cement paste with partial GBFS substitution and mixed with magnetic water has a higher degree of hydration than that with 0% substitution and prepared with tap water. This is because the magnetic force can break up the water molecules, which can then penetrate more easily into the cement particles, allowing a more complete hydration process to take place.

4. Conclusions

(1) The use of magnetic water can improve the compressive strength of mortar samples containing GBFS in place of cement. The extent of increase is dependent on the magnetic field strength of water. When the magnetic water is of 0.8, 1.2, or 1.35 T, the compressive strength of mortars increases 9–19%.

(2) With longer curing age, the trend of increase in compressive strength of mortar samples prepared with magnetic water is similar to those mixed with tap water.

(3) The compressive strength of concrete with GBFS substitution is higher than that containing no GBFS. At the same age, this increase in compressive strength becomes more significant with increasing GBFS substitution percentage. Similarly, with the same amount of GBFS added, the increase in compressive strength will become more prominent with increasing age.

(4) The W/B ratio also has an effect on the compressive strength of mortar prepared with magnetic water. The trend of change is similar to that of mortar mixed with tap water.

(5) Regardless of the content of GBFS, the fluidity of fresh mortar prepared with magnetic water is better than that prepared with tap water.

(6) Magnetic water can bring about a 10–23% increase in the compressive strength of concrete. The greatest increase can be achieved when the magnetic water is of 0.8 or 1.2 T.

(7) Concrete samples prepared with tap water and with magnetic water all show a similar trend of increase in compressive strength with longer curing age.

(8) At 7 days, there is no significant difference in the compressive strength of concrete substituted partially with 5% GBFS and that containing no GBFS. The compressive strength decreases with increasing GBFS content. However, at 28 and 56 days, the compressive strength of concrete containing GBFS is higher than that of concrete containing no GBFS. The greatest increase can be observed at 15% GBFS substitution.

(9) With the same mixture proportioning, concrete samples prepared with magnetic water will have a higher degree of hydration than samples prepared with tap water.

5. Suggestions

To achieve a better understanding of concrete mixing, the following topics are worth further investigation and study. (1) Whether there are differences in the porous structure between mortar made with magnetic water and that made with tap water. (2) Effect of addition of paramagnetic material in the mixing water on properties of concrete. (3) Effect of magnetic water on concrete prepared with chemical admixture added. (4) Influence of magnetic water on the mechanical strength of concrete containing fly ash or silica fume.

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