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Mechanical And Permeability Properties Of Boron-Modified-Active-Belite (Bab) Cement Concretes Under Different Curing Regimes

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Abstract

The cement manufacturing process requires a high energy consumption. On the other hand, one of the major environmental problems that are faced in this process is the emission of greenhouse gases into the atmosphere. Therefore, the researchers have been investigating the ways to mitigate such problems. Considerable energy savings and reduced CO_2 emission are known to be possible during the manufacture of boron modified active belite (BAB) cement. However, the properties of this type of cement have not widely been known, yet In this study, some mechanical and permeability features of BAB cement concretes exposed to distinct onset curing conditions were investigated and compared to that of ordinary Portland cement concretes. Mechanical features were evaluated by compressive and splitting tensile strength developments while the durability features of concretes were measured by means of rapid chloride penetration and water sorptivity tests. Test results showed that BAB cement concretes had almost similar strength properties with the Portland cement concretes. According to the durability test results, however, BAB cement concretes had superior permeability characteristics when compared to Portland cement concretes.

Keywords: Boron modified active belite cement; Curing regimes; Mechanical properties

Boron Modifiye Aktif Belit Çimentolu Betonların Farklı Kür Rejimleri Altında Mekanik Ve Geçirimlilik Özellikleri

Özet

Çimento üretim süreci, yüksek enerji tüketimi gerektirir. Diğer taraftan bu süreçte karşılaşılan büyük çevresel sorunlardan biri de, sera gazlarının atmosfere yayılmasıdır. Bu nedenle, araştırmacılar bu tür sorunları azaltmanın yollarını araştırmaktadırlar. Bor modifiye aktif belit (BAB) çimentosu üretimi sırasında önemli miktarda enerji tasarrufu ve daha az CO_2 emisyonu olduğu bilinmektedir. Bununla birlikte, bu tip çimentoların özellikleri henüz büyük ölçüde bilinmemektedir. Bu çalışmada, farklı başlangıç kür koşullarına maruz bırakılan BAB çimentolu betonların bazı mekanik ve geçirgenlik özellikleri araştırılmış ve normal portland çimentolu betonlar ile karşılaştırılmıştır. Mekanik özellikler basınç ve yarma dayanım gelişimleri ile değerlendirilirken, betonların dayanıklılık özellikleri hızlı klorür geçirimliliği ve kılcal su emme testleriyle ölçülmüştür. Test sonuçları, BAB çimentolu betonların mukavemet özelliklerinin normal portland çimentolu betonlarınkilerle neredeyse aynı benzerlikte olduğunu göstermiştir. Ancak dayanıklılık testi sonuçlarına göre, BAB çimentolu betonların normal portland çimentolu betonlarına kıyasla daha yüksek geçirgenlik özelliklerine sahip olduğudur.

Anahtar kelimeler: Borlu aktif belit çimentosu; Kür koşulları; Mekanik özelikler

1. Introduction

Regarding the developments for providing a sustainable technology, energy savings and protection of natural resources are the most important concerns in environmental issues. Cement manufacturing industry is in charge of 8% of the total CO2 emissions into the atmosphere [1,2]. Through the production of Boron Modified Active Belite (BAB) cement. This cement not only energy saving but also a reduction in CO2 emissions would be possible.

Because manufacturing the BAB cement require the clinkering temperature of around 1325°C which is relatively less than that required for the conventional Portland cement. Due to the fact that C_3S is not formed in the production of BAB cement, approximately 10% energy saving can be achieved, thus leading to a decrease in CO_2 emissions up to 25% [3].

Boron has been used in many different applications in industries which are included fertilizers, corrosion inhibitors, pharmaceuticals, and insecticides. Boron contains some important minerals such as Borax, Kernit, Ulexit, Colemanite, Pandermite and Hydroboraxide. Colemanite mineral is available in Turkey, USA, Argentina, Kazakhstan, and China. However, USA and Turkey are the main producers of this mineral [5-7]. The compounds (CaO, B_2O_3, and SiO_2) existing in the chemical structure of Colemanite ore can be used as raw materials for the production of cement. Colemanite does not contain alkaline minerals so that Boron cement can be utilized for the environments where there is a severe alkali-silica reaction. Despite the properties of the BAB cement has not yet been well known, BAB cement which is a sort of Portland cement named boron modified active Belite cement was standardized by Turkish Standard Institution. Although Turkey is known to have about 75% of the total earth boron deposits, utilization of Boron in cement industry has not yet been wide enough. Moreover, limited studies regarding this issue have been reported in the literature [3,8].

In the light of these facts, the aim of this study is to inquire the effects of initial curing on the mechanical and durability concerned with features of the concretes with Boron Modified Active Belite (BAB) cement. The results were contrasted with the control concretes made with ordinary Portland cement.

2. Experimental Details

2.1 Materials

BAB (Boron-Modified-Active-Belite) cement was taken from Denizli BAB cement manufacturing plant located in the Mediterranean Region of Turkey. CEM I 42.5R ordinary portland cement was used, complying with Turkish standard TS EN 197-1 [9]. The chemical compositions and physical features of the Portland and BAB cement used in the study are given in Table 1.

The fine and coarse aggregates that were taken local sources were used in the experiments. Features of these aggregates are given in figure 1.

Table 1. Chemical compositions and physical features of Portland Cement and BAB cement

Item	Portland Cement	BAB Cement
SiO_2 (%)	19.73	19.10
Al_2O_3 (%)	5.09	4.68
Fe_2O_3 (%)	3.99	3.42
CaO (%)	62.86	57.1
MgO (%)	1.61	1.32
SO_3 (%)	2.62	2.68
Na_2O (%)	0.18	0.86
K_2O (%)	0.80	0.78
Cl^- (%)	0.01	0.001
Insoluble residue (%)	0.24	0.70
Loss on ignition (%)	1.90	3.82
Free lime (%)	0.57	--
Specific gravity (g/cm³)	3.14	3.09
Setting time, Vicat needle	2-46/3-44	2-25/3-00
Le chatelier (mm)	1	0.5
Specific surface area (m^2/kg)	327	356

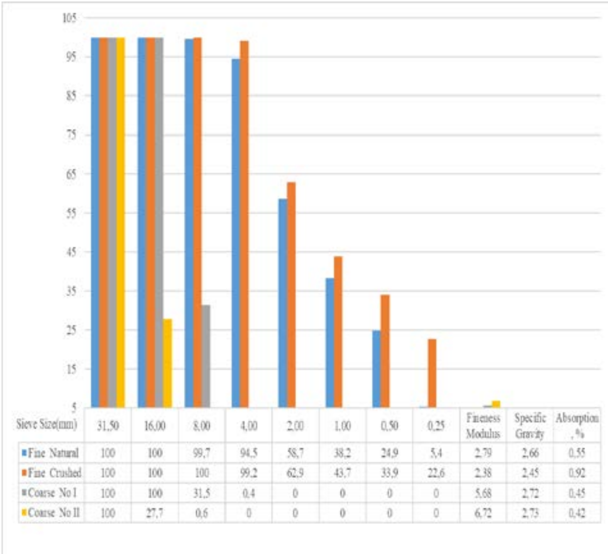

Figure 1. Sieve analysis and physical features of aggregates

2.2 Concrete mixtures

Two series of control mixtures with w/c ratios of 0.35 (Series 1) and 0.55 (Series 2) were conceived. BAB cement concrete mixtures were also designed for the aforementioned series. Therefore, totally four different mixtures given in Table 2 were prepared in the study. Grading of the aggregate mixture was kept constant for all concretes. The superplasticizer was added at the time of mixing to obtain the specified workability at each w/cm ratio.

2.3 Casting and Curing Conditions of Test Specimens

All of the concretes were mixed as defined in ASTM C192 standard. Specimens cast from each mixture consisted of fifteen cubes (150x150x150 mm) for compressive strength, four cylinders (100x200 mm) for sorptivity, six cylinders (150x300 mm) for splitting tensile strength, and four cylinders (100x200 mm) for chloride ion permeability measurements for each curing regimes.

Table 2. Mixture proportions of the concrete in kg/m³

Materials		Concrete series			
		Series 1 (w/cm=0.35)		Series 2 (w/cm=0.55)	
		Portland Cement Concretes	BAB Cement Concretes	Portland Cement Concretes	BAB Cement Concretes
Cement		450.0	450.0	350.0	350.0
Water		157.5	157.5	192.5	192.5
Fine Aggregate	Natural Sand	741.0	741.0	727.8	727.8
	Crushed Sand	92.6	92.6	91.0	91.0
Coarse Aggregate	No I	648.4	648.4	636.8	636.8
	No II	370.5	370.5	363.9	363.9
Superplasticizer		4.50	4.50	3.50	3.50

Therefore, the total number of the specimens are four times of aforementioned values. All of the specimens were placed into the steel moulds in two layers, each of which being vibrated for a couple of seconds. All of the moulded specimens were covered with a plastic sheet and left in the casting room for 24 hours. After mould removal, the specimens were divided into four groups for different curing regimes. The details of the curing regimes are as follows.

1) Initially water curing (IW): Specimens were kept in the water for 6 days thereafter they were taken out of water and left in air to cure continuously in the laboratory under ambient condition until the test age. The temperature was reasonably controlled at 20^{O}C, while the humidity that generally ranged between 50 to 80% was uncontrolled. The specimens exposed to this curing condition were designated as IW and were called initially water cured concretes.

2) Permanent water curing (PW): Specimens which were left to cure perpetually in water at 20± 2 ^{O}C till the test age exposed to this curing condition was designated as PW and were called permanent water cured concrete.

3) Initially high temperature water curing (IH): In that curing condition, the specimens were cured for 6 days in the water at temperature of 35± 2 ^{o}C then they were kept in air to cure perpetually in the laboratory under ambient condition until the test age. The specimens cured under this condition were designated as IH and were called initial high temperature water cured concretes.

4) Initially Burlap curing (IB): Specimens were cured 6 days under wet burlap followed by curing in air as IW and IH concretes until test age. These kinds of specimens were designated as IB and were called initially burlap cured at ambient temperature.

The concretes cast in the study were not only designated according to the initial curing condition but also to the cement type of either PC (Portland Cement) or BABC (Boron Modified Active Belite Cement). For instance, BABC-IB represents the concrete produced with BAB cement and initially cured under wet burlap.

3. Results and discussion

3.1 Compressive Strength

The compressive strength developments of these concretes are shown in Figure 2. It was monitored that the overall compressive strength of the concretes at 0.35 w/c ranged from 44 to 55 MPa and from 58 to 71 MPa for the samples tested at 7 and 90 days, respectively.

At a w/c ratio of 0.55, however, the concretes had compressive strengths of 23 to 29 MPa and 35 to 52 MPa, at the ages of 7 and 90 days, respectively. Test results suggested that for all of the concrete types, the permanent water curing provided the best compressive strength development, irrespective of w/c ratio and cement type. The lowest compressive strength was obtained for the concretes exposed to IB curing regime. Moreover, the concretes produced with BAB cement seemed to be more susceptible to IB curing, especially at 0.35 w/c ratio. In case of this curing, the compressive strength development of the BABC-IB concretes was slightly lower than that of PC-IB concretes. However, a higher w/c ratio of 0.55 caused higher compressive strength of BABC-IB concretes compared to that of PC-IB concretes. For example, 90-day compressive strengths of the PC and BAB cement concretes with w/c ratio of 0.35 were measured as 61 and 58.5 MPa, whereas the concretes with 0.55 w/c ratio had 90- day compressive strength values of 35 and 41 MPa, respectively.

The concretes exposed to IH curing had the highest early age strength values without depending on w/c ratio and cement type.

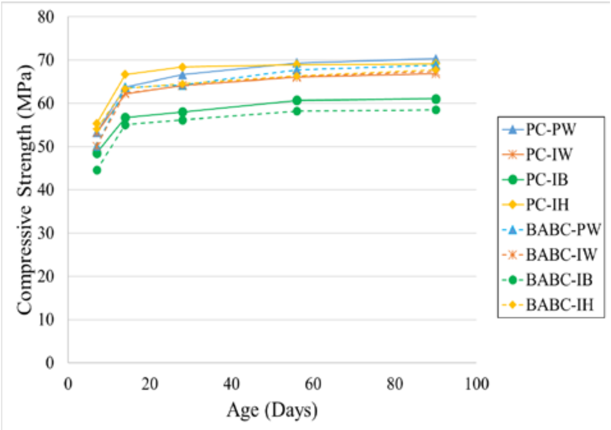

Figure 2. Compressive strength development of concretes produced with w/c ratios of 0.35

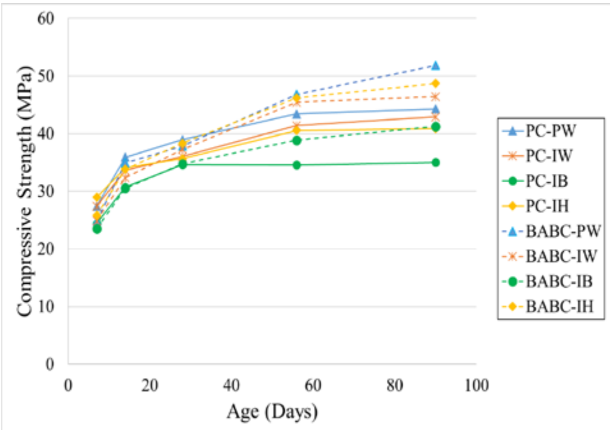

Figure 2. Compressive strength development of concretes produced with w/c ratios of 0.55

Nevertheless, the compressive strength values of the concretes under PW curing condition reached to that of IH cured concretes at 28 days. At later ages (56 and 90 days), however, the highest compressive strength values were observed at PW cured concretes. This finding was more pronounced for the concretes produced with BAB cement. For instance, BABC-PW and BABC-IH concretes at a w/c ratio of 0.55 had similar compressive strengths at 28 days. At later ages, on the other hand, there was a remarkable change in the strength values. BAB cement concretes were observed to be more vulnerable to the curing condition, particularly at high w/c ratio so that the concretes containing PC demonstrated better compressive strength development than BAB cement concretes, for a given initial curing condition. BAB cement concretes at w/c ratio of 0.55, however, exhibited better performance than PC concretes in terms of compressive strength development for all initial curing regimes. The highest 90-day compressive strengths were measured as 52 and 44 MPa for BABC and PC concretes exposed to permanent water curing. A similar finding was reported by Sağlık et al. [3]. They reported the compressive strength development of the BAB and portland cement concretes beginning from 2 days to 365 days. The overall compressive strengths of PC and BAB cement concretes ranged from 26 to 58 MPa and from 17 to 74 MPa, respectively. When considering the compressive strength development, the curing regimes can be put in order from best to poor one as PW, IH, IW, and IB, irrespective of w/c ratio and cement type.

3.2 Splitting Tensile Strength

Splitting tensile strengths of the concretes containing PC and BAB cements were presented in Figure 3.

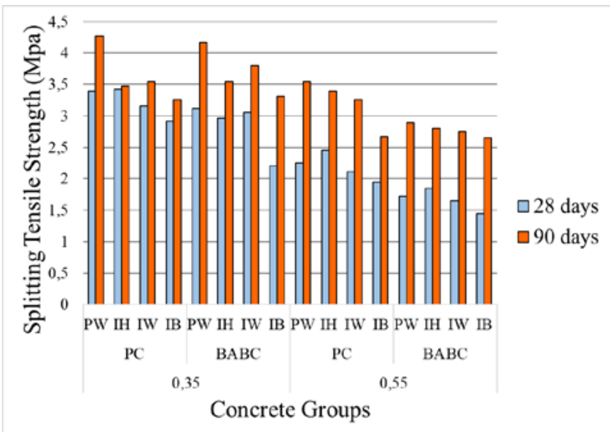

Figure 3. Splitting tensile strength development of concretes according to cement type, w/c ratio, and curing regimes

It was examined that 90-day splitting tensile strengths of the PC concrete were almost akin to BAB cement concretes at low w/c ratio. On the other hand, the PC concretes with 0.55 w/c ratio had higher splitting tensile strengths than BAB cement concretes, irrespective of the initial curing regimes. For example, at 0.35 w/c ratio, PC and BAB cement concretes under IH curing condition had 90-day splitting tensile strengths of 3.47 MPa and 3.55 MPa, respectively. However, the strength of the former and the later exposed to the same curing condition at 0.55 w/c ratio were 3.39 and 2.80 MPa, indicating a 17 percent reduction with the use of BAB cement. When considering the splitting tensile strength developments, the effect of curing regime as in the compressive strength alike. Therefore, the curing regimes may be put in order from the best to poor one as PW, IH, IW, and IB irrespective of w/c ratio and cement type.

In the study of Sui et. al. [10], the compressive and splitting tensile strengths of the high belite cement (HBC) concretes were studied. They reported that the development trend of the splitting tensile strength of HBC concrete with age is similar to that of compressive strength, namely, lower early strength, equivalent 28 day strength and higher late strength compared PC concretes.

3.3 Sorptivity

The variation in sorptivity index of the concretes produced with PC and BAB cements are shown in Figure 4.

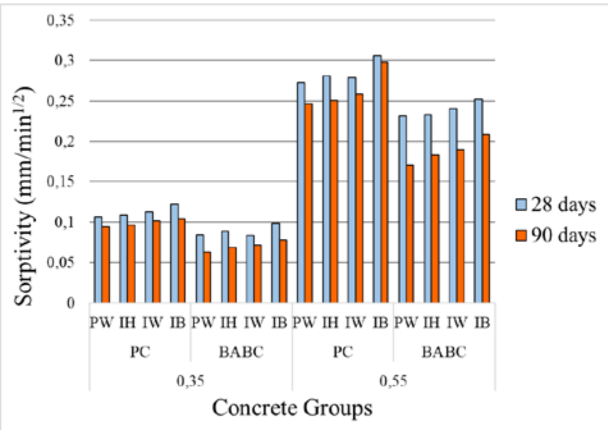

Figure 4. Variation of sorptivity coefficients of concretes according to cement type, w/c ratio, and curing regimes

It was observed that there was a systematic decrease in the sorptivity with prolonged curing period from 28 to 90 days. This effect was more influential in the case of BAB cement concretes. For instance, sorptivity of PC-IB concrete displayed a 2.5% reduction while BABC-IB concrete experienced about 17 % drop in the sorptivity as the curing period had been extended from 28 to 90 days. As a matter of the fact that the BAB cement had lower hydration kinetics than Portland cement [3,10], the change in 28 and 90-day sorptivity values of BAB cement concretes were observed to be more pronounced than PC concretes. At w/c ratio of 0.55 and 28 days, the overall sorptivity coefficients of PC concretes ranged from 0.272 to 0.305 mm/min1/2, while the those of BAB cement concretes ranged from 0.231 to 0.251 mm/min1/2, irrespective of curing condition. At 90 days, however, PC and BABC concretes had sorptivity of 0.245 to 0.298 and 0.170 to 0.208 mm/min1/2, respectively. It is obvious that BAB cement concretes had lower sorptivity than PC concretes, irrespective of curing condition and time. When the concretes were exposed to 90-day permanent water curing, the reduction in the sorptivity of the concretes with the use of BAB cement was as high as 30 %. A similar result was observed in the case of high w/c ratio concretes in that the reduction in the sorptivity was about 33 %. This behavior may be attributed to the fact that BAB cement has better pore refinement property than Portland cement. Due to the higher amount of C_2S content in BAB cement compared to PC, there is a further hydration reaction at later ages to form additional tobermorite gel. This situation leads in better matrix structure resulting in lower capillary water transport. Because, lower the permeability of the concrete, better the pore structure of the concrete as reported in the literature. [11-14].

3.4 Rapid Chloride Permeability

Test results related to the resistance of PC and BAB cement concretes against chloride ion penetration are presented in Figure 5. The reduction of the w/c ratio from 0.55 to 0.35 reduced the rapid chloride ion permeability in both concrete groups in the same line with the literature.

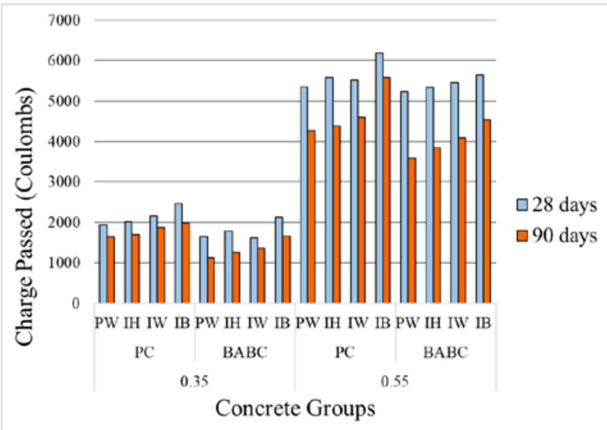

Figure 5. Variation of chloride ion permeability of concretes according to cement type, w/c ratio, and curing regimes

As in case of water sorptivity, chloride ion permeability of the concretes demonstrated a systematic reduction with an increase in curing period from 28 to 90 days, particularly in the event of concretes included BAB cement. The change between 28 and 90-day total charge passed were much higher in BAB cement concretes than PC concretes. Indeed, in the case of 0.55 w/c ratio and permanent water curing period, PC concretes had a chloride ion permeability of 5353 and 4271 Coulombs at 28 and 90 days, respectively, indicating a 20% reduction. However, the total charge passed for the companion BAB cement concretes were 5231 and 3587 Coulombs at 28 and 90 days resulting in a reduction in the chloride ion permeability of as high as 31%. It is obvious that the curing t time was more effective on the BAB cement concretes. Irrespective of curing condition, time, and w/c ratio, BAB cement concretes had lower chloride ion permeability than PC concretes. By using BAB cement, the total charged passed for the concretes having 0.55 w/c ratio and permanent water curing reduced by as much as 2 and 16 % at 28 and 90 days, respectively. However, the reduction in the chloride ion permeability appeared to be more pronounced at low w/c ratio, especially at 90 days. Indeed, 90 –day chloride ion permeability of the concretes decreased from 1643 to 1125 Coulombs, leading to a reduction of as high as 32 %.

The concretes with w/c ratio of 0.35 were generally classified as low chloride permeability concretes according to ASSHTO T277-89. However, the concretes exposed IB curing condition illustrated moderate chloride ion permeability. Whilst the lowest charges passed were measured at the PW cured concretes, the highest values were observed at IB cured concretes, independent of cement type and w/c ratios. However, the concretes with 0.55 w/c ratio and 28 day curing were rated as high chloride permeability concretes according to ASSHTO T277-89. Nevertheless, according to 90 day RCPT values, only BAB-PW and BAB-IH concretes had moderate chloride permeability. This finding suggested that even at high w/c ratio, harmful effect of chloride ions may be mitigated to some extent by using BAB cement. Although there are limited studies in the literature regarding the durability features of active belite cement concretes, some supporting results with the finding of the current study have been reported. For example, Sui et al. [10] studied some durability properties of high belite cement (HBC) concretes. They concluded that HBC concretes show better freeze-thaw resistance, higher chloride permeability resistance, carbonation resistance and less shrinkage compared with PC concretes. In the study of Sağlık et. al. [3] some durability tests like water permeability and chloride penetration resistance tests were applied to the concretes produced with BAB cement. They reported that the concrete specimens that are constituted via BAB cement depicted more resistance as the benchmarking to the specimens that are constituted via ordinary Portland cement even at lower cement contents.

3.5 Statistical Assessing of Results of the Test

A general linear model analysis of variance called GLM-ANOVA was exerted to investigate the variation in the measured features of the concretes. In this analysis, the significance levels at 0.05 levels were examined. Therefore, compressive, splitting tensile strength, sorptivity, and chloride ion permeability of the concretes were appointed as the dependent variables while the types of the cement used, curing the condition, w/c ratio, and testing age were the factors. Analysis was exerted to determine p-level<0.05 factors. These factors which are the effect on test outcomes are given in Table 5.

Table 5. Statistical Evaluation of Test Results

Dependent variable	Source of variation	Statistical parameters					Significant	Contribution %
		Degree of freedom	Sum of square	Mean square	F	p-value		
Compressive Strength	Cement Type	1	0.10	0.10	0.01	0.0926	NO	-
	w/c Ratio	1	12684.20	12684.20	2183.92	0.000	YES	79
	Curing	3	617.80	205.90	35.46	0.000	YES	3.8
	Age	4	2763.80	691.00	118.97	0.000	YES	17.2
	Error	70	406.60	5.80				
Splitting Tensile Strength	Cement Type	1	0.8192	0.8192	13.21	0.001	YES	5.6
	w/c Ratio	1	6.3013	6.3013	101.64	0.000	YES	43.2
	Curing	3	1.6234	0.5411	8.73	0.000	YES	11.1
	Age	1	5.8482	5.8482	94.33	0.000	YES	40.1
	Error	25	1.5499					
Water absorption	Cement Type	1	0.182467	0.182467	883.89	0.000	YES	88.7
	w/c Ratio	1	0.01494	0.01494	72.37	0.000	YES	7.3
	Curing	3	0.002808	0.000936	4.53	0.011	YES	1.4
	Age	1	0.005433	0.005433	26.32	0.000	YES	2.6
	Error	25	0.005161	0.000206				
Chloride ion penetration	Cement Type	1	80742661	80742661	998.04	0.000	YES	90.5
	w/c Ratio	1	1503486	1503486	18.58	0.000	YES	1.7
	Curing	3	2047811	682604	8.44	0.000	YES	2.3
	Age	1	4930389	4930389	60.94	0.000	YES	5.5
	Error	25	2022537	80901				

The percentage effect ensures an opinion of the grade of the influence of independent factors on the measured reaction. So, in the event of the contribution is higher, the effect of factors on the certain reaction is higher. Similarly, it is also the same if it is low. It was monitored in Table 5 and the cement type had no substantial effect on the compressive strength. However, there was a considerable influence of using BAB cement on particularly sorptivity and chloride ion permeability of the concretes as well as a moderate effect on the splitting tensile strength. The contribution of cement type on the variation in sorptivity and chloride ion permeability was as significant as about 90%. When compared to that of the cement type, the effects of curing condition and the testing age appeared to be remarkably lower. It was very amazing that the w/c ratio was found to be quite significant on the strength properties, but its effect was very lower in the case of permeability related properties of the concretes. Therefore, it was the cement type that governed the variation in the sorptivity and the chloride ion permeability of the concretes.

4. Conclusions

The following consequences can be deduced according to the experimental outcomes obtained in the current study.

1. Although compressive strength development at low w/c ratio were observed to be higher in PC concretes, the BAB cement concretes at high w/c ratio exhibited relatively better performance. When considering the compressive strength development, the curing regimes can be put in order from best to poor one as PW, IH, IW, and IB, irrespective of w/c ratio and cement type.

2. Splitting tensile strength development of BAB cement concretes agreed well with those PC concretes at low w/c ratio. Yet, the strength of the former was slightly lower at high w/c ratio.

3. BAB cement concretes had outstandingly lower sorptivity coefficient than PC concretes, without taking into account of testing age and curing condition. This may be attributed to the higher amount of C_2S content in BAB cement compared to PC so that there is a further hydration reaction at later ages to form additional tobermorite gel. This situation leads in better matrix structure resulting in lower capillary water transport.

4. Chloride ion permeability of the concretes showed a parallel pattern to that monitored in the sorptivity. Indeed, the total charge passed was considerably lower in the case of BAB cement concretes.

5. Both mechanical and durability features of the concretes seemed to more fluctuated due to the curing condition. Yet, BAB cement concretes were observed to be more susceptible to the curing regime adopted.

6. GLM-ANOVA reasonably verified the effects of the cement type, w/c ratio, curing regime, and

testing age on the properties of as it was seen in experimental test results.

Thus, a good compatibility among the qualitative and statistical analysis could be achieved.

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