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Investigating the effects of red mud and GGBFS industrial waste on the compressive strength of high-strength green concrete

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Introduction: The construction of green concrete is of utmost importance, due to its high compatibility with the environment, and also because of the reduction in the environmental side-effects related to the manufacture of materials used in concrete construction.

Material and methods: The current investigation made use of red mud and ground granulated blast furnace slag (GGBFS) as supplementary material to cement, in order to study their effects on the compressive strength of ordinary and early high strength concretes within various water to binder ratios (w/b). The required tests were designed using DX7 software, meaning to optimize the three variables of red mud percentage, slag percentage, and w/b ratio. Eighteen mixes were produced within 7, 28, and 56 days, according to the test design.

Results and discussion: The produced concrete specimens demonstrated an optimized red mud and slag amount of 15%, 10% and 7.5%, 20%, with the w/b equaling 0.3 and 0.375, respectively, keeping pace with the standards of both normal and early high strength concretes, in terms of strength.

Conclusion: The optimized mixes obtained in the current study were able to achieve a strength of about 90 MPa. The above indicates the suitability of red mud and GGBFS as supplementary materials to cement.

Keywords: Red mud, GGBFS, High strength concrete, Compressive strength.

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Introduction

Concrete is probably the most extensively used construction material in the world. However, when the high range water reducer or super plasticizer were invented and began to be used to decrease the water/cement (w/c) or water/binder (w/b) ratios rather than to be exclusively used as fluid modifiers for normal-strength concretes, it was found out that in addition to improvement in strength, concretes with very low w/c or w/b ratios also demonstrated other improved abrasion resistance and better durability. This fact led to the latest development in concrete that is high performance concrete (HPC). It has become more popular these days and is being used in many prestigious projects (Kumthekar *et al*., 2007). As the concrete industry developed over time, industrial wastes were more frequently used in concrete construction, in order to reduce the cost and energy, as well as to protect the environment and resources. However, the damage caused by carbon dioxide emission, as well as the extraction of raw materials during cement manufacture has brought about pressures to partly substituted cement with supplementary materials.

A variety of industrial wastes and admixtures are used in the development of HPC mixes, in order to obtain higher performance, as well as to lower the expenses. Some of the more frequently used materials include red mud, Grand Granulated Blast Furnace Slag (GGBFS) (Rajamane *et al*. 2003), copper slag (Khalifa *et al*. 2019), Cement Kiln Dust (CKD) (Gayathri and Rajasekhar, 2017), fly ash and micro silica (Amer Saleh, 2018) and other cementitious materials (Elahi *et al*., 2010). These materials increase both the strength and the durability of the HPC by reducing the permeability.

Replacing natural raw materials with wastes may offer a much sought after opportunity to mitigate today's waste management problems. Even if this is done in small amounts, high production rates will translate into significant consumption of waste materials and for the industry willing to use them, the latter may constitute a cheap and renewable source of raw materials (Raupp-Pereira *et al*., 2007a). In this context, upgrading industrial wastes to alternative raw materials is both technically and economically advantageous for a wide range of applications (Dondi *et al*., 1997), including the fabrication of concretes and mortars (Raupp-Pereira *et al*., 2007b). In recent years, several studies have confirmed the potential of civil construction as a suitable recipient of various types of recycled wastes, which are now considered secondary raw materials (Pascoal *et al*., 2000; RIS, 1998). Red mud (bauxite residue) is a solid waste generated in alumina refining from bauxite (Liu *et al*., 2014).

Red mud is usually discharged as a highly alkaline slurry (pH 10-13.5) with 15-40% solids, which is pumped away for suitable disposal. Its chemical and mineralogical composition may change temporarily, depending on the source of bauxite and on the technological processing conditions. Red mud is composed of six major oxides: Al_2O_3, Fe_2O_3, Na_2O, SiO_2, CaO, and TiO_2, and a large variety of minor elements. Due to its strong alkalinity (Na_2O + NaOH = 2.0 – 20.0 wt. (%)), the conditions in which it can be discarded are restricted to minimize environmental problems such as soil contamination and groundwater pollution (Ribeiro *et al*., 2010).

Alkaline matrices such as those provided by Portland cement in mortars and concrete are commonly used in waste conditioning. They are inexpensive, have an extensively documented history of safe use, and are a draw-upon readily-accessible technology. Alkalinity greatly reduces the solubility of many hazardous inorganic species and inhibits microbiological processes. Moreover, since these matrices require water for hydration, they may readily incorporate wet wastes such as red mud (Glasser, 1997).

ÇELiK (2017) investigated the utilization of Red Mud (RM) with Portland Cement (PC) in soil grouting. The maximum unconfined compressive strength was obtained from the grouted and pure grout samples composed of 15% red mud and 85% Portland cement. Incorporating the red mud

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with Portland cement increases the consumption of portlandite ($Ca(OH)_2$) formed during cement hydration. Lee *et al*. (2011) studied composites with blast furnace slag and red mud as a substitute for cement and observed that the fluidity and the mechanical properties are more dependent on the SiO_2 ratio than the water/binder ratio. Pan *et al*. (2002), on the other hand, evaluated a new kind of alkali-slag-red mud cementitious material and found that hardened cement paste mostly consisted of C-S-H gel, being very low in the Ca/Si ratio, very fine in size and extremely irregular in shape. Portlandite, Aft or zeolite products have not been detected, and these characteristics are considered the main chemical reasons for the high early and ultimate strength and good resistance to chemical attacks. Wu *et al*. (1990) evaluated the early age activation of BFS and blends of slag and Portland cement (OPC) using different kinds of sodium compounds as activators (Wu *et al*., 1990). Lim (2004, 2005, 2008) investigated the strength properties of slag powder on high strength concrete and found that the addition of Nano slag modified the microstructure and improved the strength of concrete. Vijaya and Dhinakaran (2014) conducted detailed experimental investigations on GGBFS based high performance concrete to study its compressive strength and sorption characteristics. In addition, natural fine aggregate was replaced with M-Sand with different proportions. They found concrete with GGBFS and M-Sand yield better results than conventional mix both in terms of compressive strength and sorptivity.

Red mud modifies significantly the workability of the mixture and does not significantly delay the hydration process of mortar (Senff *et al*., 2011). The only industrial plant for alumina production in Iran is placed at Jajarm which uses the Bayer process. This report presents the results from a study of the possibilities of using red mud, a waste product derived from the digestion of bauxite with the Bayer process and GGBFS as an additive in HPC.

Material and methods

The material used in concrete construction
Sand and gravel

Crushed sand and gravel were used in the current study with a maximum size of 20 millimeters. Particle size Distributions were as demonstrated in Figure 1.

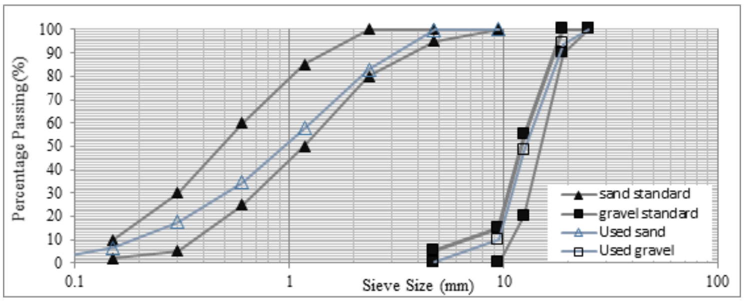

Fig. 1- Sand and gravel gradation diagram

Cement and Red mud

The cement used was type 1-525 from the cement factory of Shahrekord, the specifications of which are demonstrated in Table 1. The required red mud was sampled from five different spots in the tailings dam of Jajarm's alumina factory in North Khorasan. Then, the mixed samples were transferred to the laboratory for further analysis. The maximum particle size of applied red mud in this study was 0.15 mm (passed through sieve #100). Table 2 demonstrates the results of the tailings' oxide analysis conducted via an XRF analyzer. The results indicated remarkable amounts of Aluminum, Titanium, Iron, and Silicon compounds in the red mud. According to the chemical analysis results, the above-mentioned red mud consists of high amounts of Fe_2O_3, Al_2O_3, and SiO_2, meaning that this industrial waste might be classified as well and a suitable supplementary cementitious material.

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Table 1. The chemical specifications of cement type 1-525 (percent)

Cement type 1-525	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total alkali	LOI	Cl	F.CaO	I.R
	20.3 ±0.2	5.65±0.15	3.3±0.15	65.7±0.2	≤1.6	≤2.8	≤0.7	≤1.3	≤0.03	≤1.8	≤0.65

Table 2. The chemical specifications of red mud and GGBFS (percent)

Material	MnO_2	K_2O	Na_2O	MgO	CaO	TiO_2	Fe_2O_3	SiO_2	Al_2O_3
Red mud	-	insignificant	3.52	1.61	20.58	6.57	24.15	13.91	16.91
GGBFS	1.45	0.6	0.45	10.8	37	3.5	0.6	36	9.5

Isfahan GGBFS

The slag of Isfahan blast furnace was used in this study, with the maximum particle size of 5 micron, and with chemical specifications as demonstrated in Table 2.

Analyses and procedures

In order to investigate the quantity of oxides in the red mud as well as in GGBFS, XRF analysis was performed using a SIEMENS SRS3000 device.

Experimental design and the mix design of the concrete samples

The current study was designed through DX7 software, with the purpose of investigating the three parameters of a) the percentage of GGBFS**,** b) red mud percentage, and c) water to binder ratio, and with the aim of their optimization to achieve the highest compressive strength. Red mud was used in this investigation, with three weight percentages of 0, 7.5, and 15, and GGBFS was used with the three weight percentages of 0, 10, and 20, as substitutes for cement. Table 3 demonstrates the mixing design of the 18 developed tests.

Specimens preparation

The samples were constructed in 100*100*100 mm molds. The specimens were cured while being immersed in a water reservoir, and their compressive strength was measured on days 7, 28, and 56.

Determining the specifications of the concrete samples

The slump test was carried out using the ASTM C143 standards, in order to assess the workability of the fresh concrete. Also, the test was conducted in accordance with 3206 Iranian standards in order to determine the compressive strength of 7, 28, and 56 days old concrete samples.

Results and discussion

Slump and compressive strength tests results

The results related to the slump of all fresh concrete specimens are presented in Table 4. Also, Table 4 indicates the results related to the compressive strengths of the concrete samples on days 7, 28, and 56. Figure 2 presents a comparison between the specimens of different ages.

Analysis of results

Using DX7 (Design Expert v7.0) software, the results of the compressive strength tests were analyzed and the suitable range was determined for achieving the maximum compressive strength, using three variables of red mud, GGBFS, and w/b ratio. The three graphs in Figures 3, 4, and 5 refer to the 0%, 7.5%, and 15% red mud used as a substitute for cement. The graphs demonstrate changes in the compressive strength of the concrete as a function of w/b ratios and slag percentages, and through curves with the same compressive strength. The maximum amount of total substitution in the mixes in this study was limited to 27.5%; however, the software conducted the required analysis for up to 35% of slag and red mud substitution, presented in Figure 5. As the curves indicate:

a)The compressive strength of the 7, 28, and 56 day old samples increased with the decrease of w/b ratio amount, as predicted.

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Table 3. The experimental design and mix design of concrete specimens

Mix	RM (%)	Slag (%)	W/B (%)	Total replacement of cement (%)	Cement (Kg)	RM (Kg)	Slag (Kg)	Sand (Kg)	Gravel (Kg)	SP (%)
1	7.5	0	37.5	7.5	406.4	32.95	0	846.9	1044.91	2
2	15	0	37.5	15	373.5	65.90	0			
3	0	0	30	0	439.4	0	0			
4	0	0	45	0	439.4	0	0			
5	0	10	37.5	10	395.5	0	43.93			
6	0	20	45	20	351.5	0	87.87			
7	15	10	30	25	329.5	65.90	43.93			
8	7.5	10	37.5	17.5	362.5	32.95	43.93			
9	7.5	10	30	17.5	362.5	32.95	43.93			
10	7.5	10	45	17.5	362.5	32.95	43.93			
11	7.5	20	30	27.5	318.6	32.95	87.87			
12	7.5	20	45	27.5	318.6	32.95	87.87			
13	15	10	37.5	25	329.5	65.9	43.93			
14	0	0	37.5	0	439.4	0	0			
15	7.5	20	37.5	27.5	318.6	32.95	87.87			
16	0	20	37.5	20	351.5	0	87.87			
17	15	0	45	15	373.5	65.9	0			
18	15	10	45	25	329.5	65.9	43.93			

Table 4. The slump and compressive strength test results for all the 7, 28, and 56 day old samples

Mix	Replacement (%)			W/B (%)	Slump (mm)	Compressive strength test (MPa)		
	Total	**Slag**	**Red mud**			**(day 7)**	**(day 28)**	**(day 56)**
1	7.5	0	7.5	37.5	90	56.65	67.3	76.84
2	15	0	15	37.5	100	48.3	59.05	70.04
3*	0	0	0	30	10	76	79.8	90.60
4*	0	0	0	45	170	50.05	53.55	59.33
5	10	10	0	37.5	160	62.5	72.4	74.88
6	20	20	0	45	165	49.75	59.35	68.08
7	25	10	15	30	40	63.5	78.1	86.42
8	17.5	10	7.5	37.5	145	60.2	69.6	74.47
9	17.5	10	7.5	30	30	69.25	76	88.17
10	17.5	10	7.5	45	150	47.05	54.4	60.87
11	27.5	20	7.5	30	80	63.6	75	85.28
12	27.5	20	7.5	45	175	45.5	55.2	58.61
13	25	10	15	37.5	150	57.2	60.4	66.23
14*	0	0	0	37.5	160	60.05	73	79.31
15	27.5	20	7.5	37.5	150	56.3	69.3	75.09
16	20	20	0	37.5	165	53.85	64.8	75.91
17	15	0	15	45	160	47	50.3	56.65
18	25	10	15	45	155	44.8	54	58.09

* Samples 3, 14, and 4, are control samples (with no red mud and slag) for w/b ratios of 0.3, 0.375, and 0.45, respectively.

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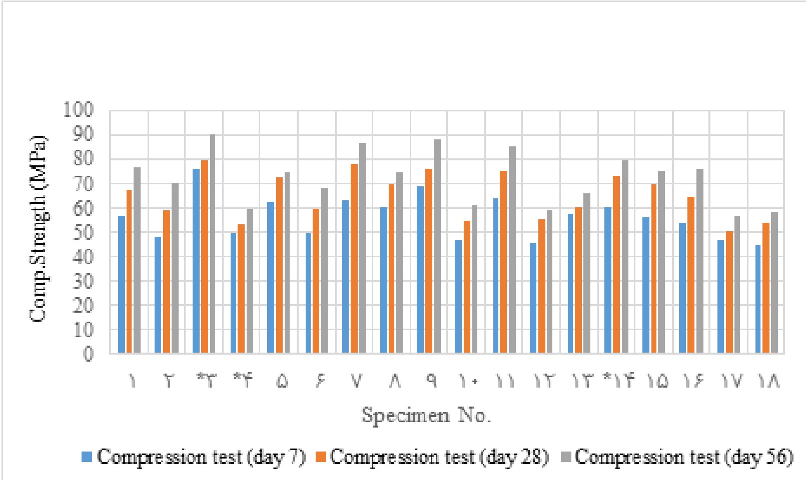

Fig. 2- The comparison of compressive strengths of the 7, 28, and 56 day old samples

b) The compressive strength of the 56 day old samples decreased, as the percentage of red mud substitution increased, provided that the two parameters of slag and w/b ratio were kept constant.

c) Provided that the amount of red mud used is 15%, the increase in slag amount increased the strength in low w/b ratios (0.3), while it caused a decrease in the compressive strength of the 56 day old specimens, in high w/b ratios (Figure 5).

d)Provided that the amount of red mud used was 0%, the slag increase led to strength decrease in 56 day old concrete in a low w/b ratio (0.3)—with the maximum decrease in 20% slag equaling about 6 MPa, whereas in a high w/b ratio (0.45), the increase in slag led to a rise in strength in 56 day old specimens (Figure 3). The slag increase did not cause any significant changes.

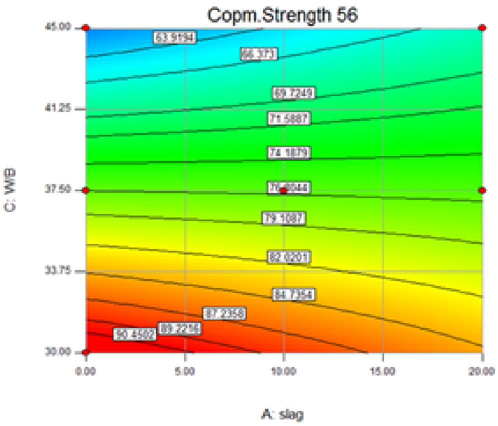

Fig. 3- with 0% red mud substitution

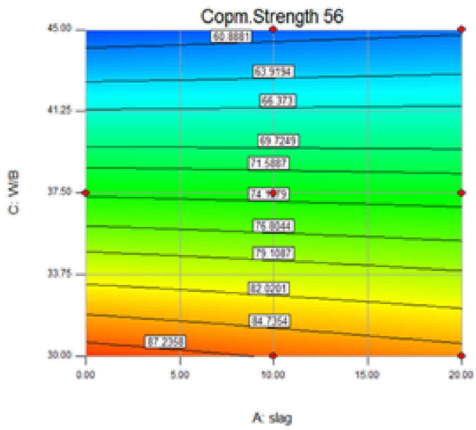

Fig. 4- with 7.5% red mud substitution

Curve demonstrating the changes in the compressive strength of the 56 day old concrete as a function of the w/b ratio and slag percentage

e)The optimized mixing amount with regard to compressive strength and substitution percentage in the w/b ratio of 0.3, equaled 15% red mud and 20% slag. However, considering the results of previous studies regarding the maximum substitution amount of cement with various additives, the optimized substitution percentage for the total amount of wastes (additives) was kept as low as 25% (15% red mud and 10% slag), as a precaution.

f)The optimized mixing amount was considered to be 7.5% red mud and 20% slag in the w/b ratio of 0.375, resulting in a 25% substitution of cement.

g)The optimized mixing amount with regard to strength only in the w/b ratio of 0.45 would be 15-

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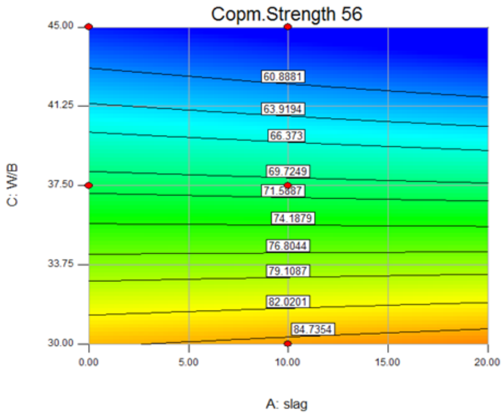

Fig. 5- Curve demonstrating the changes in the compressive strength of the 56 day old concrete as a function of the w/b ratio and slag percentage (with 15% red mud substitution)

20% slag and no red mud, resulting in a 15-20% cement substitution.

h)In optimized conditions, the compressive strength in the w/b ratios of 0.3 and 0.375 indicated a mere 5% decrease in comparison with the control sample, which is considered insignificant in comparison with the 25 to 27.5% decreases of the consumed cement.

According to code nine of the Iranian National Building Regulations (INBR) about high strength concretes (Iranian National Building Regulations, 2013), and with regard to the ACI-ASCE committee 441, the low and high levels of strength for high strength concretes are considered to be 50 and 70 MPa, respectively (ACI-ASCE Committee 441, 1996). Also, according to the above-mentioned regulations, the strength of normal high strength concretes is determined by the compressive strength of 56 day old samples, as the compressive strength of 28 day old specimens determines the strength of high early strength concretes.

The maximum and minimum amounts of strength were demonstrated via horizontal lines on the bar chart in Figure 6. The strength of all the 56 days old mixes in the experiment was above 70 MPa, specifically samples with red mud and slag placing them among the HSCs. Moreover, as Figure 2 demonstrates, the 28 days old compressive strength of all the specimens fell within the range of 50 to 70 MPa, indicating that all the constructed mixes may also be used as high early strength concretes, according to code nine INBR requirements.

Table 5 presents the amount of cement used in various mixes with different cement substitution ranging from zero to 35%, for each of the w/b ratios of 0.3 and 0.375. As explained earlier, all those samples were categorized as either normal or early HSCs. According to code nine of the National Building Regulations, the minimum amount of cement for high strength concretes must be 390 kg/m^3; this is while the obtained samples demonstrated an extremely higher strength in comparison with the highest level in HSCs using less cement, which is in itself proof for the satisfying performance of red mud and GGBFS as substitutes for cement.

Conclusion

The current investigation made use of red mud (0-15%wt.) as a substitute for cement for the first time in Iran and also used red mud along with GGBFS (0-20%wt.) as cement substitutes. The main results of the study were as follows:

1) The optimized amount of red mud and slag were respectively 15% and 10% in the w/b ratio of 0.3, and 7.5% and 20% in the w/b ratio of 0.375. The compressive strength of the sample in the optimized circumstances indicated a 5% decrease

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in comparison with the control sample (with no wastes); however, it is still higher than the maximum compression strength determined by code nine of the INBR (70 MPa). It is noteworthy that this amount of decrease in strength is considered insignificant in comparison with the economic and environmental advantages which follow the 25 to 27.5% decrease in the cement consumed.

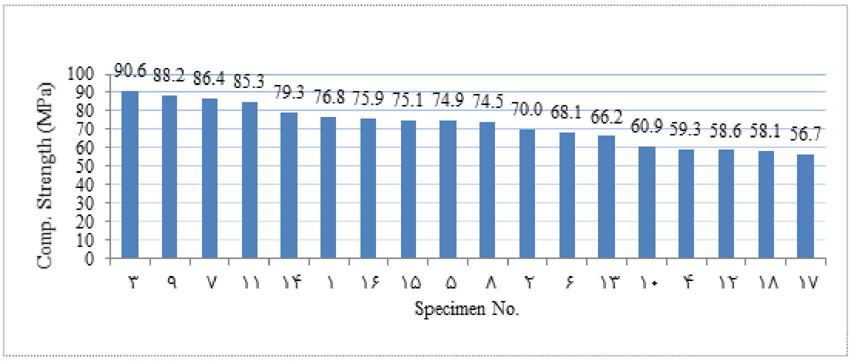

Fig. 6- Bar chart demonstrating the compression strength of the 56 days old samples

2) A comparison between the obtained compressive strengths revealed that the 28 day old compressive strength of the specimens constructed through optimized mixing was completely within the range of early HSCs.

3) The obtained mixes in the current study were able to achieve an extremely higher strength in comparison with the highest level of strength in HSCs, which was 70 MPa with less than the minimum amount of cement determined by code

Table 5. The total percentage of red mud and slag replacement and its effect on the compressive strength of the normal and early HSCs (56 days old and 28 days old, respectively)

Mix	Cement replacement	W/b	Cement (kg)	(56 day old) Compression strength (MPa)	(56 day old) **Compression strength decrease (%)	(28 day old) Compression strength (MPa)	(28 day old) **Compression strength decrease (%)
3	0	0.3	439.4	90.6	-	79.8	
9	17.5		362.5	88.17	2.7	76	4.8
7	25		329.5	86.42	4.6	78.1	2.1
11	27.5		318.6	85.28	5.9	75	6.0
Via software	35		285.6	86.5	4.5		
14	0	0.375	439.4	79.31	-	73	-
1	7.5		406.4	76.84	3.1	76	-4.1
5	10		395.5	74.88		72.4	
2	15		373.5	70.04		59.05	
8	17.5		362.5	74.47	6.1	69.6	4.7
13	25		329.5	66.23	16.5	60.24	17.5
15	27.5		318.6	75.04	5.4	69.3	5.1
Via software	35		285.6	69.7			

Mixes 7 and 15 represent the optimized total amount of red mud and slag percentages replacing cement in the w/b ratios of 0.3 and 0.375, respectively.

** Decrease in comparison with the control sample (%)

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nine of the INBR (390kg/m^3). This is an indicator of the satisfying performance of red mud and GGBFS as cement substitutes.

4) The tests designed via DX7 for the sake of this study were meant to investigate the three parameters of w/b ratio, red mud percentages, and slag percentages. The tests resulted in curves indicating the behavior of the three parameters, which are considered to be important components in determining the parameters' optimized amounts in various strength, economic, and environmental circumstances.

5) The results of compressive strength showed that the amount of red mud in concrete affected the behavior of slag in various water to cement ratios.

6) Economically, exploiting red mud and GGBFS in concrete as cement substitutes will lower the total cement price, considering the insignificant prices of red mud and GGBFS in comparison with those of other cement additives, especially concrete. Furthermore, from an environmental point of view, exploiting the above-mentioned tailings in concrete construction will lower environmental pollutions and the use of fossil fuels (due to the decrease in cement construction) on one hand, and a decrease in maintenance and management costs, on the other.

پی‌نوشت

Aft Phase: Ettringite (Al_2O_3-Fe_2O_3 trisulfate)

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بررسی تاثیر پسماندهای صنعتی گل قرمز و GGBFS بر بتنهای سبز مقاومت زیاد

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سابقه و هدف: ساخت بتن های سبز از منظر سازگاری مناسب آن با محیط زیست و از منظر کاهش اثرات زیست محیطی ناشی از تولید مصالح مورد استفاده در ساخت بتن از اهمیت ویژه برخوردار است.

مواد و روشها: در پژوهش حاضر، از گل قرمز و سرباره ذوب آهن به عنوان جایگزین سیمان استفاده شده تا عملکرد آنها را بر مقاومت فشاری بتن های پر مقاومت معمولی و زودرس تحت w/b های مختلف مورد بررسی قرار دهد. با هدف بهینه سازی سه متغیر درصد گل قرمز، درصد سرباره و w/b، آزمایش های مورد نیاز با استفاده از نرم افزار DX7 طراحی شدند و ۱۸ اختلاط متناظر با این طراحی آزمایش ساخته شد و طی ۷، ۲۸ و ۵۶ روز عمل آوری و آزمایش شد.

نتایج و بحث: با توجه نتایج حاصل از بارگذاری نمونه های بتنی ساخته شده، مقدار بهینه گل قرمز و سرباره در w/b معادل با ۰٫۳ و ۰٫۳۷۵ به ترتیب برابر (۱۵٪ و ۱۰٪) و (۷٫۵٪ و ۲۰٪) تعیین شده است که از نظر مقاومت فشاری، همزمان استاندارد بتن های پرمقاومت معمولی و زودرس را تامین می نماید.

نتیجه‌گیری: طرحهای اختلاط بهینه بدست آمده در این تحقیق، توانسته به مقاومتی حدود ۹۰ مگاپاسکال دست یابد. که این مهم، خود نشان از عملکرد خوب گل قرمز و سرباره ذوب آهن به عنوان جایگزین سیمان می باشد.

واژه‌های کلیدی: گل قرمز، سرباره کوره ذوب آهن اصفهان، بتن مقاومت زیاد، مقاومت فشاری.

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