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Experimental Evaluation of The Impact Resistance of Alkali-Activated Slag Concrete Under High Temperature

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ABSTRACT

In recent years, the use of activated alkaline slag concretes (AASC), has had a wide perspective in civil engineering science due to its many environmental benefits (due to the reduction of the emission of CO2 gas in the air) and high resistance to impact loads. is in this article, a mixed design of ordinary portland cement concrete (OPCC) containing 500 kg/m3 of portland cement as a control concrete and a mixed design of AASC containing granulated blast furnace slag (GBFS) was made, and the impact resistance of the concrete was tested under the weight-drop impact test (WDIT). It was evaluated at temperatures of 21, 300 and 600 ℃ at the age of 90 days. The obtained results indicate that the increase in temperature has caused a drop in the results of the WDIT, so that in OPCC, the energy absorbed and the flexibility index of concrete samples at a temperature of 600 ℃ drop by 76.92% and it obtained 86.95% improvement compared to 21 ℃ temperature, while in active alkali concrete, these figures brought 66.66 and 14.28% drop in results, respectively. In this regard, the number of impacts required for the occurrence of initial cracks and failure in the concrete sample had a downward trend with increasing temperature. In this experimental research, AASC showed superior results compared to OPCC. The results obtained from the analysis of the images of the scanning electron microscope (SEM) on the concrete samples overlapped with the other tests of this research.

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1. Introduction

In line with the development of national security and passive defense in the field of civil engineering infrastructure, many laboratory works have been done to produce structural concrete in strategic and sensitive centers of the country [1-3]. The strength of the reinforced concrete structures of these centers plays an important role in reducing destruction and human injuries caused by the enemy's defense operations. Improving the strength of concrete can be achieved through the type of materials used in its mixture [4-10].

Ordinary cement production has always brought environmental concerns due to the consumption of mineral resources, fossil fuels, and the production and emission of poisonous carbon dioxide gas. Research has shown that cement factories are responsible for the release of about 5% of the total carbon dioxide entering the earth's atmosphere

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[11]. In order to solve these problems, alkali active concrete which does not use cement was proposed by the researchers. In the production process of this type of concrete, aluminosilicate materials and active alkali solution replace ordinary cement, the final product of this combination is the production of a large volume of hydrated gels with high adhesion and filling characteristics in the matrix of activated alkali cement. Alkaline cements are a group of active alkali materials, materials that show superior engineering properties compared to Portland cement [12]. On the other hand, the amount of carbon dioxide produced in the production process of alkali-active materials is much lower than the production process of ordinary cement [13].

According to yerde's theory, the fireproof property of concrete is perhaps the most important point in the safety of structures, and this is the property that fully reveals the advantages of concrete in this field, therefore, in concrete structures, protection against Rupture against excessive heat is provided at the same time [14]. The results of the research conducted on the effect of heat on AASC showed that there are no significant changes in the mechanical properties of concrete under the temperature of 27 to 100 ℃, a decrease of up to 40% in the mechanical properties of concrete, after applying A temperature of 350 ℃ occurs in the early stages, and it has also been reported that the exit of water from the chemical bonding space in hydrated calcium silicate (C-S-H) leads to the failure of concrete at a temperature of more than 450 ℃ [15]. In general, it is believed that activated alkalis perform better than OPCCs in facing fire due to their ceramic characteristics [16-18]. The resistance of AASC when exposed to heat depends on the chemical composition of the concrete constituents, as well as the temperature and the way it is processed [19].

Impact resistance can be investigated by several types of tests, including explosion test, projectile impact test, pendulum impact test, and WDIT. Impact loads are divided into two groups of impact with low speed and impact with high speed according to the impact speed. One of the advantages of carrying out impact test is to determine the failure energy of the samples, the failure energy is one of the most important indicators of the science of fracture mechanics. High fracture energy is a sign of resistance of samples against crack propagation. Researches have shown that, in concrete exposed to impact, microcracks extend ahead of the crack tip and create the area of the fracture process that originates from local strain [14]. If the degree of compaction in the microstructure of concrete is high, the propagation of microcracks against impact loads is delayed. Superior impact resistance of weight-drop type in activated alkali concrete compared to OPCC has been reported in many researches [20-22]. In line with the application of high heat to concrete samples, with the increase of temperature and consequently the increase of cracks on the surface of the sample, the concrete becomes crystalline or hollow and becomes very fragile against impact [23]. The objectives and innovation in this laboratory research through the production of alkali-active concrete can be summarized as follows:

1. The mechanical and microstructural properties of alkali activated concrete are improved compared to OPCC.
2. Helping to reduce the volume of toxic carbon dioxide gas emissions compared to OPCC production, according to the report provided by other researchers in this regard.
3. Helping to maintain the health of the environment by using (in the composition of activated alkali concrete) slags accumulated in iron smelting factories, known as environmentally harmful substances.
4. Maintaining and reducing the consumption of mineral resources that are used as the main materials during the process of making ordinary cement.
5. Maintaining and reducing the consumption of fossil fuels that are used as fuel in conventional cement factories.

2. Materials

In this laboratory research, type 2 Portland cement produced by Gilan Sabz Cement Industries (Diylman) with a density of 3250 kg/m3 and a specific surface area of 3000-3200 cm2/g, produced under the ISIRI 389 standard, was used. The slag of the metallurgical furnace, a product of Isfahan iron smelting factory, with a density of 2750 kg/m3, a specific surface area of 2200 cm2/g, and an apparent density of 960 kg/m3 was used according to the ASTM C989/C989M standard, the chemical characteristics of this product in Table 1 shows. The water used for the preparation of lime water and the construction of the mixture plan in the upcoming research is drinking water of Lahijan city, this water has a pH in the range of 5.6 to 5.7 and a density of 1000 kg/m3. According to clauses 9-10-4-2 and 9-10-4-3 of the fourth edition of Iran's National Building Regulations, water that is drinkable, has no specific taste and smell, and is clean and smooth can be used without testing. used in concrete, unless previous records indicate that this water is unsuitable for concrete. Consumable aggregate is synthetic and based on the requirements of ASTM C33 standard, prepared from sand factories in Lahijan city, some characteristics of the aggregate are shown in Table 2. Research has shown that fresh activated alkali concrete has a weaker performance due to the high viscosity in the activated alkali solution compared to concrete containing fresh normal portland cement. To solve this problem, a superplasticizer based on polycarboxylate is often used due to Strong bonds between calcium with positive charge and polycarboxylate with negative charge is the best option [24]. In this regard, the 4th generation superplasticizer based on normal polycarboxylate, a product of Durocham Middle East company, was used based on the characteristics of Table 3.

The activated alkali solution used in this research is a combination of sodium silicate and sodium hydroxide solution with a weight ratio of 2.5, which was used with a combined density of 1483 kg/m3. Some of the characteristics of the activated alkali solution used in this research are in Table 4 is shown.

Table 1.
Chemical Characteristics of GBFS (%)

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Tio_2	MnO	L.O.I
36.72	35.5	9.17	7.49	6.24	0.12	1.21	0.92	2.49	0.18	0.02

Table 2.
Characteristics of Aggregates

Concrete Materials	Water Absorption (%)	Density (kg/m^3)	Modulus of Softness (mm)	Maximum Diameter (mm)	Minimum Diameter
Fine Aggregates	2.9	2650	2.85	4.75	75(μm)
Coarse Aggregates	2.2	2750	5.7	19	4.75(mm)

Table 3.
Characteristics of Normal Polycarboxylate Superplasticizer

Flash Point	Chlorine Ion Content	pH	Standard	Density (kg/m^3)	Color	Physical State
Does Not Have	Does Not Have	About 7	ASTM C494	1100	Brown	Liquid

Table 4.
Characteristics of Active Alkali Solution

Molecular Formula	The weight (molar) ratio of silicate to water	The weight (molar) ratio of silicate to sodium	Molar Mass (gr/mol)	Melting Temperature (C)	Modulus of Elasticity (p)	Density (kg/m^3)	Molarity (mol/m^3)	Color
NaOH	-	-	39.99	318	3.3	2130	12	White
Na_2SiO_3	47	2.4	122.06	1088	-	2400	12	White

Table 5.
Specifications of Concrete Mix Design

Type Concrete	SuperplaSticizer	FA[1]	CA[2]	Water	GBFS	Cement	Quantity	density concrete mix (kg/m^3)	Curing conditions After mold removal	Ratio W/C
OPCC	7	765	1000	225	0	500	kg/m^3	2497	In the Water	45%
	0.0028	30.63	40.04	9.01	0	20.02	%			
AASC	7	726.63	1000	225	500	0	kg/m^3	2494.63	Heat + Dry Environment	45%
	0.0028	30.57	40.08	9.19	20.04	0	%			

- In AASC, the W/C ratio means the ratio of activated alkali solution to the slag of the used GBFS.
1- FA = **Fine Aggregates**
2- CA = **Coarse Aggregates**

3. Mix Design

There is no separate standard for the design of alkali-active concrete mix, therefore, according to some laboratory researches [25], the alkali-active concrete mix plan has been prepared and adjusted according to the standard of preparation normal concrete under the recommendation of the ACI 211.1-89 committee. The concrete mix plan in this laboratory research is shown in Table 5.

4. Construction and Curing

At first, according to the mixture plan in Table 5, the consumable materials were weighed and then the dry materials including cement (or GBFS) and aggregate were poured into the circulating electric mixer and the mixing process lasted for 1.5 minutes. ended Next, wetter materials including water (or active alkali solution) were added to the mixture and the combination of materials continued for another 2.5 minutes. Then, the fresh concrete mixture was poured into pre-oiled and foiled metal molds in three stages. In this direction, in order to apply compaction, 25 impact were given to the concrete mixture in each stage by a special rod. At the end, the molds containing concrete samples were stored in a dry environment under a temperature of 21 ℃. After this time passed, the samples were molded and the OPCC samples were stored and processed in lime water at a temperature of 21 ℃ until the time of the test. AASC samples were subjected to heat treatment at 60 ℃ after molding for 48 hours in the oven to improve the strength of this type of concrete. After this time, the concrete samples They were removed from the oven and stored and processed in a dry environment under a temperature of 21 ℃ until the time of the test. In line with heat treatment in activated alkali concrete, research has shown that samples of activated alkali concrete subjected to heat treatment at temperatures of 50-70 ℃ have greater strength than samples at temperatures of 20 ℃ [14].

5. Standard and Method of Conducting Tests

Impact resistance test of the weight-drop type at the age of 90 days according to ACI 544-2R standard on concrete disc samples with dimensions of 35.6 x 15 cm at temperatures of 21, 300 and 600 ℃ was done. This test is in the field of examining the mechanical properties of concrete and is a good criterion for measuring the resistance of structures exposed to impact loads. According to the standard mentioned in this test, the weight of the hammer is 4.54 kg, the height of the fall of the weight is 45.7 cm, and the diameter of the metal ball is 6.35 cm. To perform the test, after the curing age and during the determined thermal process, the disc samples were placed inside the impact device just under the weight drop in such a way that the metal ball is placed exactly in the center of the sample, then the number of impacts which is registered for the occurrence of the first crack (N1) and the final rupture (N2) by a counter installed in the upper part of the device. The fracture energy for the occurrence of the first crack (E1) and final rupture (E2) was calculated in terms of joules through equation 1. In this regard, N is the number of impacts to create a crack, W is the weight of the hammer, and H is the height of the fall of the weight. Before performing the high temperature tests in the WDIT, which was performed at the age of 90 days, according to the ISO834 standard, the concrete samples were placed in the oven at 300 and 600 ℃ for 1 hour. Then, the samples were left in the furnace for another 1 hour so as not to be affected by temperature shock. After the samples were taken out of the furnace, the samples were kept at room temperature for 24 hours to reach the temperature equilibrium. The use of this standard has been reported in other researches about tests under high heat in concrete [26]. SEM analysis was performed at the age of 90 days in concrete under 21 ℃ by SEM with FEI Quanta 200 model. Next, the microstructure was examined.

$$E_n = N \times W \times H \quad (1)$$

6. Results and Analysis of Tests

6.1. The Results and Analysis of the Impact Resistance Test

The results of impact test of falling weight in concrete are shown based on figures 1, 2 and 3. According to these results, it can be seen that the increase in temperature caused a drop in the results in the WDIT, so that in OPCC, the energy absorbed and the flexibility index of concrete samples under the temperature of 600 ℃ 76.92% decrease and 86.95% improvement compared to the temperature of 21 ℃, respectively, while in activated alkali concrete, these figures are 66.66% and 14.28%, respectively. accompanied the number of impacts required to cause initial cracks in concrete samples decreased with increasing temperature. So that in OPCC, the maximum (10 impact) and minimum (2 impact) number of impacts for the occurrence of initial cracks were obtained at 21 and 600 ℃. For AASC, the maximum (14 impact) and minimum (6 impacts) number of impacts for the occurrence of primary cracks were obtained at 300 and 600 ℃. The number of impacts required for the appearance of the final crack in the concrete sample had a downward trend with increasing temperature. So that in OPCC, the maximum (23 impact) and minimum (5 impact) number of impacts for the occurrence of initial cracks were obtained at 21 and 600 ℃. For AASC, the maximum (12 impact) and minimum (9 impact) number of impacts for the occurrence of initial cracks were obtained at 300 and 600 ℃. Alkali active concrete showed superior results compared to OPCC. This issue is due to the presence of aluminosilicate materials and the better pozzolanic activity of GBFS compared to Portland cement in the concrete composition, which leads to the production of a higher volume of hydrated gels such as hydrated calcium silicate (C-S-H) in the composition of activated alkali concrete. has been These gels improve compaction and strength in concrete by filling holes, pores and creating bonds in the interfacial transfer zones (ITZ) between paste and aggregate. The results of the SEM analysis on the concrete samples from this research overlapped with other tests of this research.

6.2. SEM Results and Analysis

In this research, the images obtained from the SEM imaging test at a scale of 10 micrometers are displayed in

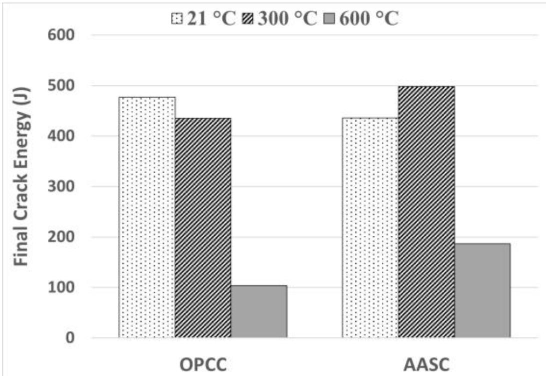

Fig. 1. The Energy Resulting from the Occurrence of the Final Crack

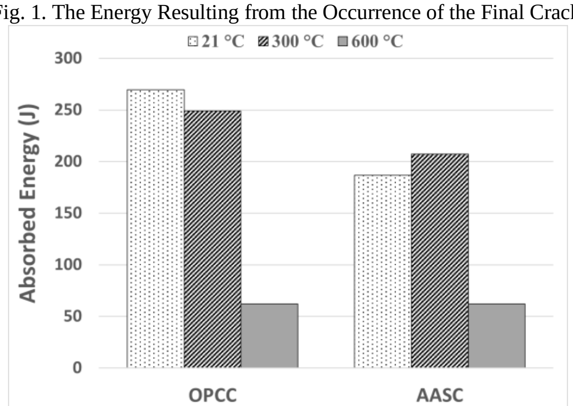

Fig. 2. Absorbed Energy

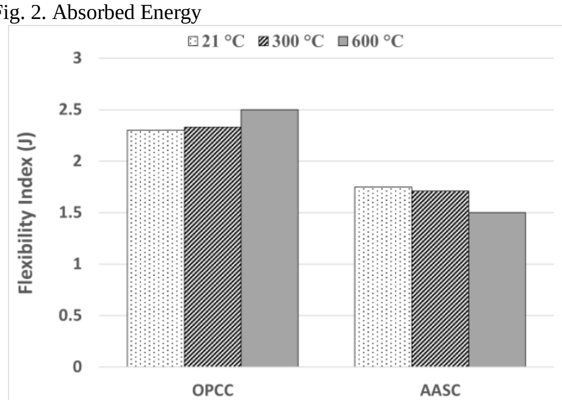

Fig. 3. Flexibility Index

Figure 4. In these images, the microstructure of concrete in mixed designs can be summarized in three basic phases:

1. The first phase includes hydration and geopolymerization products, including hydrated gels that are mainly dark in color in the pictures, these gels, after forming and in combination with other concrete components, are the main factor in strengthening the microstructure of concrete through the filling of pores and cavities, as well as the improvement of bonding in the ITZ and interlayer zones (in hydrated gels) are known.
2. The second phase includes unreacted crystals that are formed as a result of impurities in raw materials or unreacted particles in the process of hydration and geopolymerization, and they are mostly white in the pictures.
3. The third phase includes the bonding of cement paste with aggregates in the interfacial transition area, as well as the bonding of interlayers in the structure of hydrated gels.

In the images of activated alkali concrete, no tree structure can be seen that shows weakness in the microstructure of the concrete sample. In OPCC containing portland cement, more pores, holes and the volume of clinker grains of unhydrated cement are seen than in the sample of activated alkali concrete. The presence of dark colored areas in the images indicates the completion of a large part of the geopolymerization process and the production of hydrated gels. The white masses in the images of this design can be attributed to the alkaline active-forming crystals that did not participate in the geopolymerization process, and the very small points in the microstructure of activated alkali concrete can be attributed to unhydrated GBFS particles. attributed the microcracks in the picture can be considered as active alkali concrete samples due to heat treatment at 60 ℃. In OPCC, in the bulk part of Portland cement paste, ions such as calcium, sulfate, hydroxide and aluminate, which are formed through aerobic (dissolution) into calcium silicate and calcium aluminate, combine together and form a gel. They give ettringite (C-A-S-H) and calcium hydroxide (Ca(OH)2), in the sense that ettringite is created as a result of the reaction of calcium aluminate with calcium sulfate, and with the progress in the hydration stage, weak C-S-H crystals and the second generation of crystals that formed from calcium hydroxide (Ca(OH)2) and ettringite gel (C-A-S-H), they start to fill the empty spaces in the ettringite and portlandite network, and with this operation, the density, hardness, and resistance of the ITZ concrete increases [14]. The researches of others have shown that in activated alkali concrete, the pozzolanic reaction by converting CH to C-S-H condenses and homogenizes the microstructures [27]. The results of SEM analysis in this laboratory research are in full overlap and harmony with the results of other tests in this article.

7. Conclusions

In this laboratory study, the production of AASC and its comparison with OPCC was investigated, following the impact resistance test of the weight-drop type. The analysis of SEM images was also done in order to evaluate the microstructure and verify the results of other tests. The results obtained in this research are presented as follows:

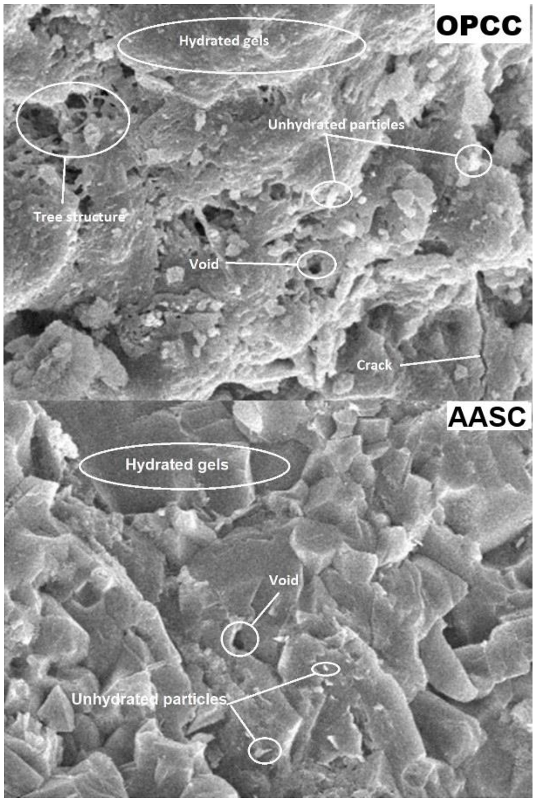

Fig. 4. Results of SEM Analysis

1. Increasing the temperature caused a decrease in the results of the WDIT, so that in OPCC, the energy absorbed and the flexibility index of the concrete samples at a temperature of 600 ℃ decreased by 76.92% and 86.95%, respectively. obtained the percentage of improvement compared to the temperature of 21 ℃, while in active alkali concrete, these figures were 66.66 and 14.28%, respectively, and the results decreased.
2. The number of impacts required to cause the initial crack in the concrete sample decreased with the increase in temperature. So that in OPCC, the maximum (10 impact) and minimum (2 impact) number of impacts for the occurrence of initial cracks were obtained at 21 and 600 ℃. For AASC, the maximum (14 impact) and minimum (6 impact) number of impacts for the occurrence of initial cracks were obtained at temperatures of 300 and 600 ℃.
3. The number of impacts required for the appearance of the final crack in the concrete sample had a downward trend with increasing temperature. So that in OPCC, the maximum (23 impact) and minimum (5 impact) number of impacts for the occurrence of initial cracks were obtained at 21 and 600 ℃. For AASC, the maximum (12 impact) and minimum (9 impact) number of impacts for the occurrence of initial cracks were obtained at 300 and 600 ℃.
4. In the impact resistance test of the weight-drop type, AASC showed superior results compared to OPCC. This issue is due to the better activity of GBFS compared to Portland cement in the concrete composition, which has led to the production of a higher volume of hydrated gels in the concrete composition. These gels improve the density and strength of concrete by filling holes and voids.
5. The results of the SEM analysis on concrete samples were in overlap and coordination with other tests of this research.

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