Mechanical Properties and Chloride Ion Penetration of Alkali Activated Slag Concrete

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Abstract. Compared to ordinary Portland cement (OPC) concrete, alkali activated compounds refer to inorganic materials that cement is not the main constituent in their mixes. In fact, alkali activated concretes have two main parts in their binder structure: source material and alkaline activator liquid. In this study, the binder consists of blast furnace slag as a source material and sodium silicate solution (wt. ratio: $SiO_2/Na_2O = 2.33$) and 6 M potassium hydroxide which are incorporated as alkaline activator liquids. Since there are several parameters that affect the properties of these concretes, 9 alkali activated concrete mix designs are utilized to investigate the influence of source material amount, solid part of alkaline activator, solid part of sodium silicate solution and the ratio of water to binder. Furthermore, one mix design for OPC concrete is performed to compare with alkali activated slag (AAS) concrete characteristics.

In this investigation, the fresh concrete properties are reported for these mix designs through slump loss test. Additionally, the compressive strength of the samples is measured at 1, 7, 28, 90 and 180 days ages. Moreover, because of the influence of chloride ion penetration that initiates corrosion of the reinforcement steel, chloride ion ingress is examined by diffusion tests based on NT Build 443. Besides, color change boundaries (CCB) in each specimen are measured to determine the penetration depth.

According to the results, mechanical properties and durability of AAS concretes are mostly influenced by the alkaline activator liquid contents and also it was observed that these characteristics development is decelerated specially by increasing the amount of activators.

Keywords: Alkali activated slag concrete · Diffusion coefficient · Chloride migration test · Alkaline activator solution · Compressive strength

1 Introduction

Today, reducing air pollution is a critical purpose for each of the industries. Production of cement is considered as one of the most pollutant industries due to the high volume of CO_2 emissions. Additionally, CO_2 is the most important greenhouse gas which leads

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to global warming. Since, cement is the main constituent in concrete structure, investigators trying to find out an appropriate solution to decrease the environmental degradations. Replacing cement by supplementary cementitious materials such as blast furnace slag could be introduced as one of the ways which decreases the negative environmental impacts of incorporating cement as a main constituent of concrete (Kazemian et al. 2015). In this method, early ages strength is commonly lesser than OPC concrete. Therefore, alkali activating of blast furnace slag with suitable amounts of activators that results in higher compressive strength at early ages, could be an appropriate approach for enhancing concrete environmental disadvantages during cement consumption process. In fact, alkali activated concretes are novel construction materials with suitable mechanical and durability properties which consist of two main parts: Source material and alkaline activator liquids. Aluminosilicates compounds such as fly ash, metakaoline, and slag are usually chosen as source materials and alkaline activators like NaOH, KOH, Na_2CO_3, and Na_2SiO_3 are employed to activate the aluminosilicate structures which result in the formation of the binder structure. In this study, blast furnace slag is utilized as source material and potassium hydroxide and sodium silicate solutions are employed to activate slag. On the other hand, according to the importance of sustainable development issues, producing durable concrete against aggressive environment is one of the significant approaches that attracted the researchers' attentions. Compared to OPC concretes, AAS concretes have many advantages. According to the investigations, high and rapid strengths can be achieved without chemical additives or special treatment by these types of concretes. In addition, lower hydration heat, superior durability and high resistance to chemical attacks are some other advantages of AAS concretes (Wang et al. 1995). Chloride ion penetration is introduced as one of the threatening factors that many researches are carried out to characterize the degradation process caused by those ions. Steel reinforcement corrosion particularly results from chloride penetration in concrete and pH reduction which activated the passive layer. Indeed, activating the passive layer around the reinforcement steel depends on the amount of chloride ions. When the amount of chloride ions is greater than the critical content, the risk of corrosion increases. In addition, according to what investigations have insisted, it is only free chloride that affects the corrosion process (Arya et al. 1990). However, there are several methods to measure the chloride penetration in concrete which are utilized to indicate the durability of concrete samples against chloride ingress. Due to what has been reported through the researches, diffusion rates in AAS concretes are lower than OPC concretes with same water to binder ratio (Hakkinen 1987). This study has concentrated on understanding the chloride ion ingress in AAS concretes and the detection of parameters which affects these properties. Besides, other properties of AAS concretes such as fresh concrete behavior and compressive strength have been controlled to compare the influence of different factors.

2 Materials and Mixing Proportion

As it was described, blast furnace slag was utilized as a source material in alkali activated concretes structure. Employed slag properties fulfilled the ASTM 989 requirements. Furthermore, type I cement was used in the mix design of OPC concrete.

Table 1. Physical properties of blast furnace slag and cement.

Specification	Slag	Cement
Specific gravity (gr/cm^3)	2.79	3.02
Fineness (cm^2/gr)	3383	3035
Amount retained on 45 μm (No. 325) sieve (%)	16.61	13.72

Table 2. Chemical composition of blast furnace slag and cement.

Material	% by mass										
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	TiO_2	MnO	L.O.I
Slag	36.75	37.21	11.56	1.01	0.97	8.52	0.61	0.7	1.23	0.99	0.02
Cement	63.78	21.55	5.89	3.72	1.89	1.35	0.53	0.3	–	–	0.94

The physical properties and also chemical composition of these materials are presented in Tables 1 and 2.

6 molar potassium hydroxide solution as one of the activators was incorporated of solid potassium hydroxide and distilled water 24 h before the concrete production. In addition, sodium silicate solution with a ratio SiO_2/Na_2O of 2.33 and solid particle ratio of 48% was used in the role of second alkaline activator. Moreover, the aggregates were categorized in three classes. Fine aggregates (natural sand) had maximum size of 6 mm, with specific gravity of 2560 kg/m^3 and water absorption of 2.89% which incorporated as 60% of total mass of aggregates. Fine gravel with maximum size of 12.5 mm, contained specific gravity of 2550 kg/m^3 and water absorption of 2.39% and employed with ratio of 0.24. Finally, coarse gravel with maximum size of 19 mm possessed 2590 kg/m^3 specific gravity and also water absorption of 2.15% and used with ratio of 0.16. It should be mentioned that all of the specific gravity amounts are stated in saturated surface dry (SSD) condition. In the main mix designs of AAS concrete a copolymer polycarboxylate-ether type High-Range Water Reducer

Table 3. Mixing proportion.

Mix design ID	Cement (kg/m^3)	Slag (kg/m^3)	W/B	Solid part of alkaline activator to slag ratio	Solid part of Na_2SiO_3 to KOH ratio
S = 300	–	300	0.4	0.15	0.6
S = 350	–	350	0.4	0.15	0.6
S = 400	–	400	0.4	0.15	0.6
w/b = 0.35	–	400	0.35	0.15	0.6
w/b = 0.45	–	400	0.45	0.15	0.6
WG = 0.4	–	400	0.4	0.15	0.4
WG = 0.8	–	400	0.4	0.15	0.8
AC = 0.1	–	400	0.4	0.1	0.6
AC = 0.2	–	400	0.4	0.2	0.6
OPC	426	–	0.4	–	–

Admixture (HRWRA) with a specific gravity of 1.1 was employed with amount of 1% of binder materials. Utilized HRWRA complies with ASTM C 494-Type G admixtures. The detailed mix designs of AAS concretes are shown in Table 3. It should be explained that the last mix design is about the OPC concrete mixture which was constructed for comparison with AAS concretes. In the AAS concretes mix designs, the solid part of activator has been considered as a part of binder and the existing water in alkaline activator solutions has been taken as a part of total water in water to binder ratio. S = 400 is introduced as control mix design and other mixes compare with that.

3 Concrete Casting

The alkali activated mixture which had been prepared in the 60 L pan mixer, were being cast in 10 * 10 * 10 cm and 15 * 15 * 15 cm cubic moulds and 10 * 20 cm cylinder moulds, immediately after the end of mixing. In this study for mixing procedure the following methodology was selected after different trials. Firstly, the aggregates and also slag were being dry-mixed. After complete integration, KOH solution was added and mixed for 30 s. Continuously, following the hand mixing and digging the bottom of the pan, water glass solution, water and superplasticizer were added and mixing process were being continued for 2 min and 30 s. Ultimately, after 24 h passed from concrete casting, the specimens were demoulded and cured in water until the ages of tests. The curing procedure had been selected through the initial compressive strength tests and also according to the previous researches about AAS concretes (Saud 2002; Collins and Sanjayan 1999).

4 Tests Conducted

To control the fresh concrete properties slump test was conducted on fresh mixtures and slump loss was recorded during periods of time after mixing process and until reaching no slump state. This test method carried out due to ASTM C143.

To discover the effects of each parameter in mechanical properties of hardened concrete, compressive strength was measured at 1, 7, 28, 90 and 180 days on AAS concrete specimens. For this test method, three 10 * 10 * 10 cm cubic specimens were placed in 2000 KN hydraulic press and loaded with the rate of 0.5 $N/mm^2/s$.

The resistance to chloride ions ingress was assessed throughout the diffusion test according to the NT- build 443 standard which is based on Fick's second law. To prepare the samples in this method, 15 * 15 * 15 cm cubic specimens were employed. The specimens at each age of the test firstly were kept in water until complete saturation (approximately 10 days). Then the specimens were coated with epoxy-based paint, except for one surface. Afterward, they were returned to the water to immerse till the complete saturation again. Then the specimens were transferred to 165 g/L NaCl solution to expose for 42 days. After this period of time, the samples to use for obtaining chloride profile are gained by grinding off specimens in layers parallel to exposed surface. By means of potentiometric titration, the chloride penetration concentrations at each depth were measured for the samples. In this research, this test was carried out at 7, 28 and 90 days of age.

Color change boundaries (CCB) test is employed to determine the depth of chloride penetration in concrete samples at ages of 7, 28 and 90 days. The preparation is similar to the diffusion test except the kinds of specimens differ from that. In this test 10 * 20 cm cylinder specimen at each age was cut to four 5 * 10 cm disks. In this methodology, at each age two disks exposed to NaCl solution for 42 days and two disks for 90 days. After these exposure times, the disks brought out and divided into two halves and left for drying. Then by spraying a 0.1 M $AgNO_3$ solution onto both halves, the color change boundaries were detected and the depth of chloride penetration was verified.

5 Results and Discussion

Fresh concrete properties. Through the test and observations, AAS concretes contain low workability and are viscous compounds. Due to the slump loss test, it can be stated that by increasing the amounts of source material (slag), the workability has been improved. In fact, the time to reach zero slumps in AAS concrete increases by using higher quantity of slag. Varying amounts of water to binder ratio have low impact on slump loss. However, by increasing water to binder ratio the duration of being in collapse state in slump test became longer comparably. By monitoring the influence of water glass to KOH ratio, the S = 400 mix design with the solid part of Na_2SiO_3 to KOH ratio of 0.6 has performed better through later slump loss than two other mixes. This might be related to the interaction of two kinds of activator and also the impact of pH on setting. Last parameter which was evaluated is the effect of alkaline activator amount. As the last results of slump loss test, it can be stated that increase in alkaline activator/slag ratio resulted in better performance of fresh concrete. The reason should be as a consequence of larger inter-particle distance and lower particle interference [Sathonsaowaphak et al. 2009]. Figure 1 demonstrates the results of slump loss test in AAS fresh concretes.

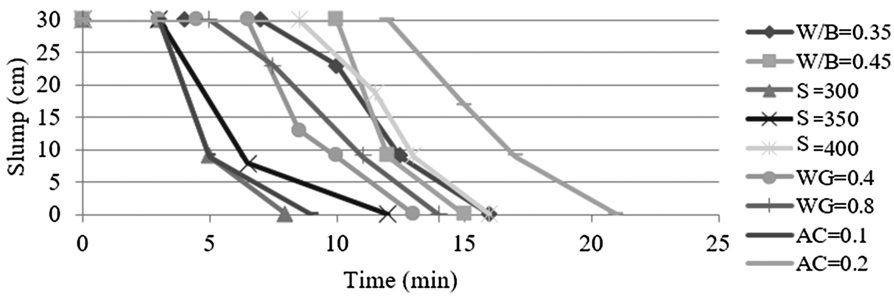

Fig. 1. The results of slump loss test.

Compressive strength. In Fig. 2 the results of all compressive tests are indicated. According to Fig. 2, the lowest value of compressive strength at 180 days age is related to w/b = 0.45 and the highest one is for w/b = 0.35.

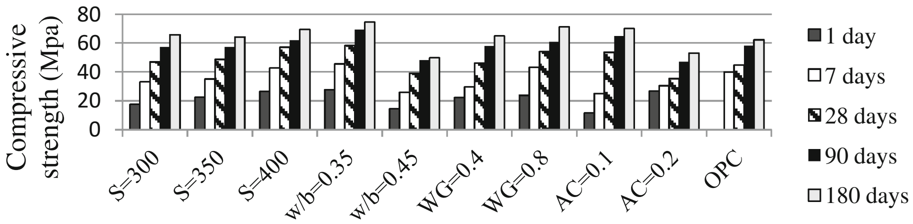

Fig. 2. Compressive strength of all mix designs.

Figure 3 shows the progress of compressive strength in detail. According to these results, the differences caused by changes in the amounts of slag are small. Just the mix design with 400 kg/m^3 of slag have slightly higher compressive strength than other mix designs. The same as OPC concretes, increasing water to binder ratio resulted in reduction in compressive strength. Regarding the effects of water glass and proportion of alkaline activators, like what displayed in Figs. 2 and 3 variations in this ratio did not have considerable influence on this characteristic of concrete particularly in long term. The most important factor which evaluated in this experiment is the alkaline activator to source material ratio. This parameter has distinctive impact in the different periods of time. In the initial ages using more amounts of alkaline activator solutions is the reason for higher compressive strength. But as time passed, decrease in alkaline activator quantity results in improving of mechanical strength.

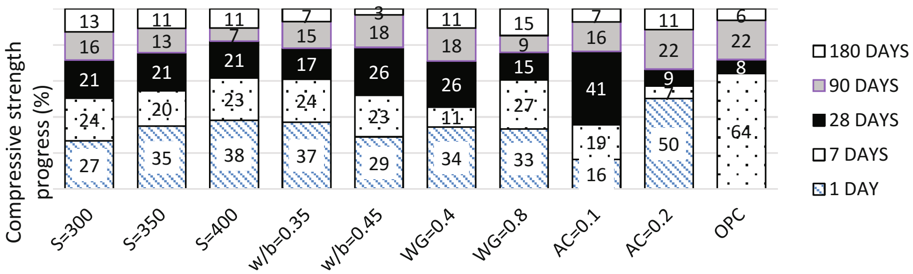

Fig. 3. The effects of different factors on compressive strength progress.

Diffusion test. The diffusion coefficients were calculated from the chloride profile. In the Fig. 4, the diffusion coefficient of all mixes at 7, 28 and 90 days can be observed. Through this investigation, it was found out that increase in source material causes a reduction in diffusion coefficient which means the better durability against chloride penetration. In three mix designs selected to evaluate the effect of water to binder ratio,

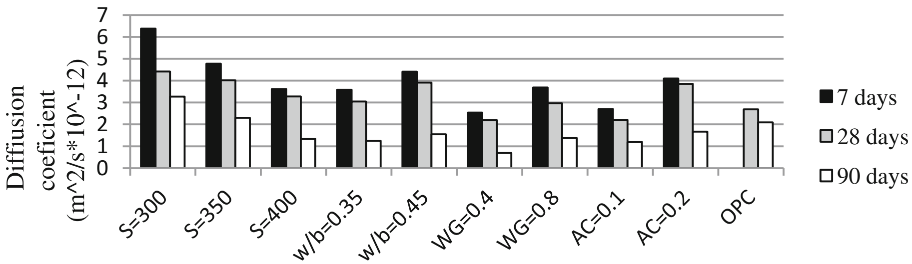

Fig. 4. The diffusion coefficient of all mixes.

the w/b = 0.45 contains the highest amount of diffusion coefficient. Whereas, two mix designs w/b = 0.35 and S = 400 have similar diffusion coefficients. As a result of comparing the impact of alkaline activator mixing proportions, the procedure of changes in diffusion coefficient is not obvious. About this procedure, it can be stated that WG = 0.4 has the lowest diffusion coefficient at all ages. It is completely clear by considering the figure that decrease in the amount of alkaline activators to slag ratio results in the reduction of diffusion coefficient. By comparing OPC concrete and AAS concrete, this conclusion can be obtained that at 28 days OPC concrete samples show lower diffusion coefficient but at 90 days AAS concrete contains lower amounts of diffusion coefficient. This could be as a result of different permeability in two kinds of concrete at these ages.

Depth of penetration due to the CCB. Since the color change boundaries was not clear and obvious in AAS samples and also the human error in measuring the depth of chloride penetration, this test is not recommended for AAS concretes. Results obtained from this test are not accurate enough. However, in almost all ages, increasing the slag content reduces the depth of penetration (See Fig. 5). In addition, the water to binder reduction brings about reduction in penetration depth (see Fig. 6). Repeatedly, the influence of water glass to KOH ratio is not clear to judge about the chloride ingress in

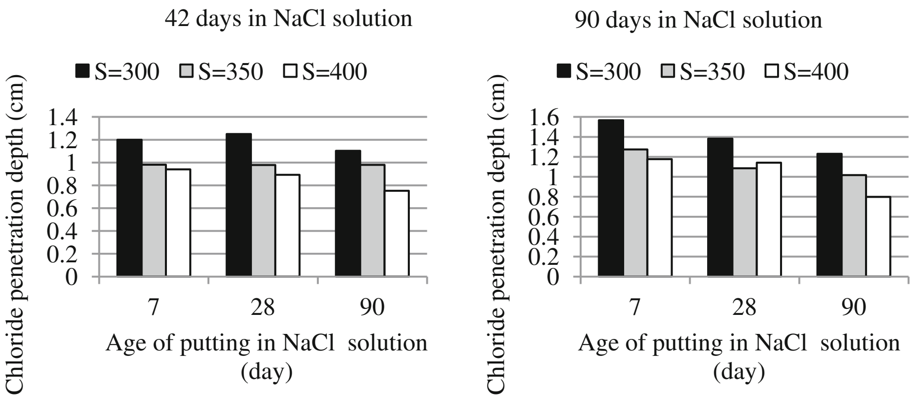

Fig. 5. Effect of source material amounts on chloride penetration depth.

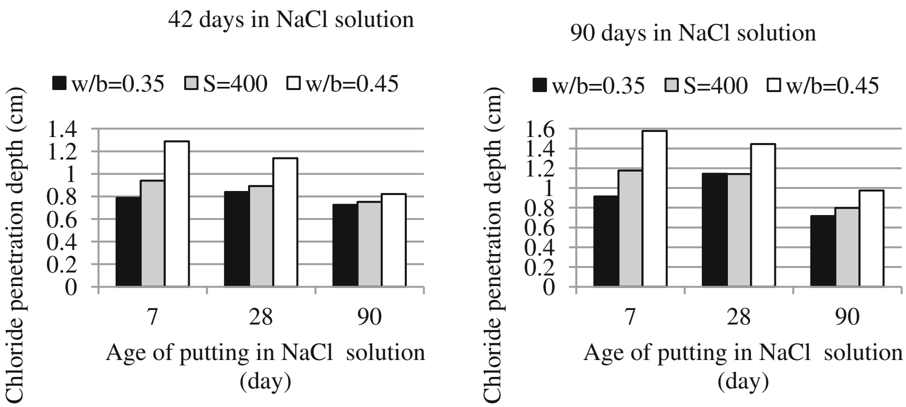

Fig. 6. Effect of water to binder ratio on chloride penetration depth.

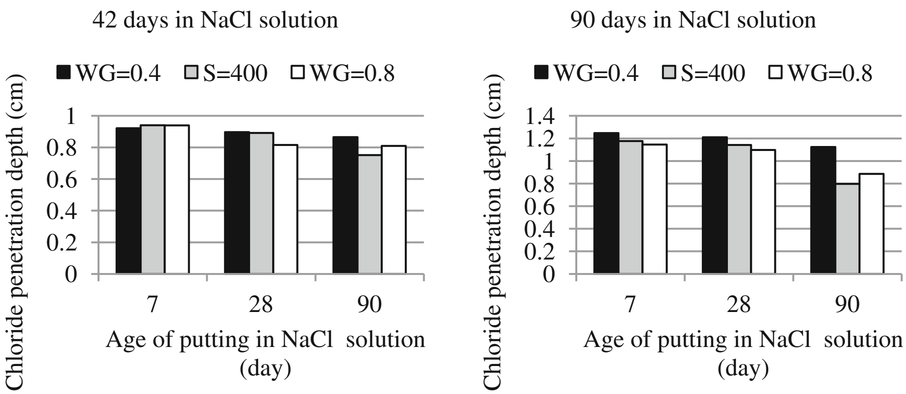

Fig. 7. Effect of WG to KOH solids part ratio on chloride penetration depth.

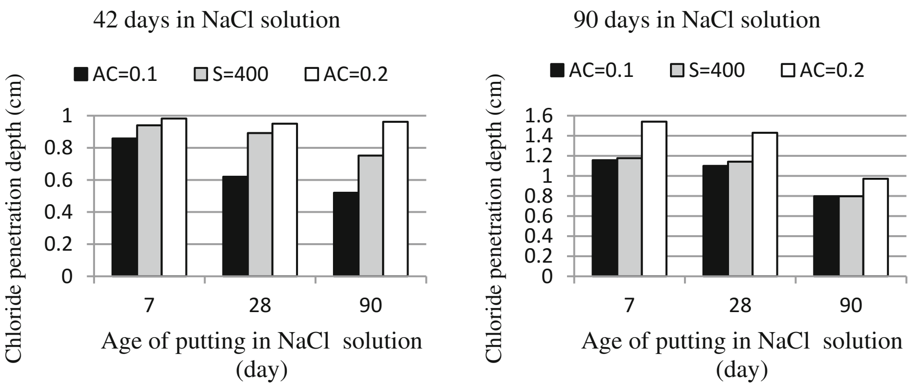

Fig. 8. Effect of alkaline activator to slag ratio on chloride penetration depth.

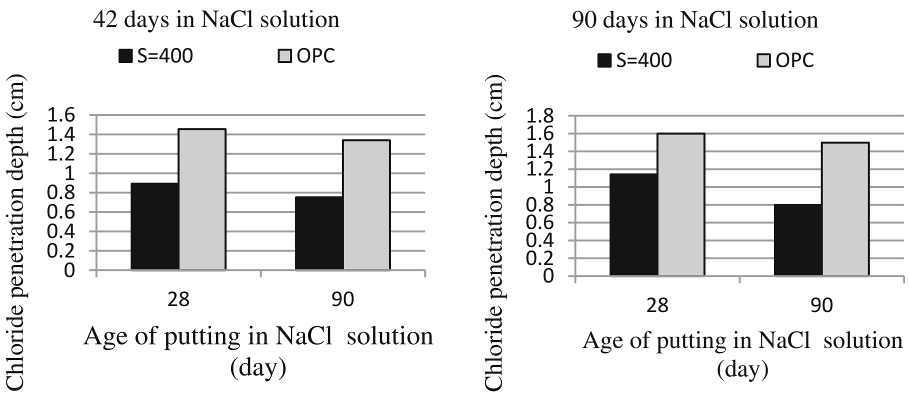

Fig. 9. Comparison of AAS and OPC concretes.

three mixes certainly. In most situations, WG = 0.8 has the minimum and WG = 0.4 has the maximum depth of penetration (See Fig. 7). Obviously, increase in alkaline activator to slag ratio show higher depth of penetration (See Fig. 8). According to the experiment, compared with OPC concrete, AAS concrete samples which refer to control mix design (S = 400) possess lower penetration depth (See Fig. 9).

6 Conclusion

In general, the following conclusion could be drawn from the study:

(1) Using blast furnace slag with the amount of 400 kg/m^3 for better fresh concrete properties, desire hardened concrete mechanical characteristic and finally appropriate durability against chloride ingress, is reasonable amount for source material in AAS concretes. (2) Decreasing water to binder ratio makes the AAS concretes to have higher compressive strength and also improves the durability of concrete against chloride penetration. (3) Decision about the chloride penetration through the observation of color change boundaries and measuring the penetration depth is an impossible work. Therefore, utilizing another test methods are necessary. (4) To decide about the effect of WG to KOH solution, it is suggested to use higher mix proportions for this ratio. (5) In contrast with fresh concrete properties, using lower ratio of alkaline activator to slag is recommended because of suitable long term compressive strength and durability. (6) According to the test results, AAS concretes have more appropriate characteristics in comparison with OPC concrete. (7) Due to the slump loss test, use of a suitable retarder is essential to have workable AAS concrete. Consequently, it is recommended to investigate about the effects of different additives and the influence of them on fresh and hardened concretes.

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