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Early and Later Age Mechanical Properties of High-Performance Alkali-Activated Slag Concrete

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ABSTRACT

Three groups of Alkali-Activated Slag AAS mixtures were investigated, where each group represents a water-to-binder W/B ratio of 0.35, 0.40 and 0.45, and alkali-to-binder ratio of 0.45, 0.55 and 0.65, respectively. Each group had two slag contents, 350 kg/m3 and 400 kg/m3. Silica modulus Ms of all the mixtures was fixed for all the mixtures, while Na2O ranged between 10% and 14%. The mixtures were cured by two curing methods; sealing in polyethylene bags, and a new curing method that is more practical and applicable on sites. The compressive strength of the AAS concrete mixtures was investigated at the ages from 6 hours to 91 days. Furthermore, indirect tensile and flexural strengths were also investigated at the age of 28 days, in addition to testing their modulus of elasticity. The mechanical properties of specimens cured by the new proposed curing method were lower than their counterparts which were cured by sealing. However, the difference is insignificant, especially if compared with the benefit and the applicability of the new curing method on site. The results show that the compressive strength of the mixtures at 6 hours reached up to 10 MPa, and at 28 days up to 98 MPa. The slump cone test of the mixtures reached up to 175 mm, while the indirect tensile strength and modulus of rupture reached up to 5.54 and 10.7 MPa, respectively. The modulus of elasticity of the mixtures was high on average where it ranged from 35.9 to 44.1 GPa.

1. Introduction

Alkali-activated slag concrete has been studied extensively due to its durability and high strength [1,2] that is comparable to or higher than Ordinary Portland cement OPC concretes, with the added benefits of its low price and lower environmental damage [3,4]. This concrete uses a type of slag called Ground Granulated Blast Furnace Slag GGBS, which showed its efficiency to be activated and used as a binding material [3,5,6].

The amount and nature of alkali activators are believed to be of the major factors that affect the strength of AAS concretes [2]. One of the major factors that affect the compressive strength of the mixtures is silica modulus, where it is believed that increasing silica modulus result in increasing their compressive strength [7]. Sodium silicate (Na_2SiO_3) or waterglass and sodium hydroxide (NaOH) showed that they are superior in activating slag [8–10]. Sodium hydroxide can be used to activate slag, but it needs to be diluted, since it is a strong alkali and using it in overdose can cause flash setting [11,12].

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Waterglass can also be used to activate slag as it is believed to show the best mechanical performance on AAS [13,14]; since it increases silica modulus. In a previous study by Puertas and Torres, at 2014 [15], they showed that using waterglass to activate slag would result in doubling the compressive strength of AAS pastes over slag pastes activated only with sodium hydroxide. They also showed that silica modulus and Na_2O equivalent are the two main factors that represent the activation and strength development of AAS. Other studies proved that increasing Na_2O equivalent, would increase the compressive strength of AAS mortars; and in parallel, the more silica modulus increase the more the strength becomes higher [16,17]. On another study [18], the compressive strength of AAS concrete mixture with 0.75 M_s, 4% Na and a liquid-to-binder ratio of 0.5, reached 16 MPa after 1 day. Some previous research reported that Na_2O percentage have a huge influence on shrinkage resulting from the formation of silica gel in hydration when waterglass is used to activate GGBS; where it caused an increase in shrinkage strains [19,20]. For that reason, most of the previous research work used activators with low percentage of Na_2O equivalent, lower than 10% [16,17,19–21]. However, another study showed that Na_2O percentage and the type of the activator nearly do not affect the shrinkage strain in AAS mortars [22].

Several curing regimes were proposed for AAS concretes and mortars, where many studies showed the advantages and disadvantages of each method. While some studies showed that high curing temperature plays a major role in increasing compressive and tensile strengths [1,23–25]; some other researchers believe that the increase is at early ages, while the later age strengths would be affected negatively [5,26]. Exposing mixtures without any type of curing has been proved to result in a strength reduction due to high drying shrinkage and massive loss of water content, which was more obvious at ages more than 3 days [27]. Sealed curing and water curing, both methods showed their effectiveness on increasing compressive strength of AAS concrete. However, sealed curing showed a better reflection on mechanical properties of AAS, especially after 7 days from casting; although the difference between the strengths of the specimens cured by both methods after 91 days is insignificant [27]. Nevertheless, sealed curing is hard to be applied practically for mass production of AAS concrete structures, that is why the other curing methods can be more advantageous, even if they do not provide a mechanical performance that is as high as the sealed curing.

In a previous study [28], different mechanical properties of three AAS concrete mixture have been tested. The three mixtures had W/B ratio of 0.28, 0.36 and 0.44, and slag content of 569.9, 440.1 and 358.5 kg/m^3, respectively. The compressive strength of the mixtures increased with the increase of slag content, and reached up to 58 MPa and up to 105 MPa, at 1 and 28 days, respectively. While slump reached up to 230 mm for the high W/B ratio. The maximum splitting tensile strength observed was almost 4.83 ± 0.12 MPa for the lowest slag content and the highest W/B ratio. While the maximum static modulus of elasticity was almost 33.90 ± 0.79.

In another study by Zidan et al., 2022 [29], 24 AAS mortar mixtures with different W/B ratios, silica modulus, and sodium hydroxide-to-waterglass. The mixtures were cured by two different procedures; sealing, and full immersion in water until testing day. The Tests showed that the highest compressive strength was for the mixtures with silica modulus of 1.2. Also, curing by sealing showed a higher 7-day compressive strength than curing by full immersion in water. However, it was noticed that curing by immersion in water showed on one of the mixtures a 3-day compressive strength that is similar to that of the 7-day compressive strength. Which can mean that curing in water at that silica modulus can make the specimens reach a very high compressive strength at a lower age.

2. Research Significance

The usage of alkali-activated slag AAS has been encouraged in the past two decades, due to its high strength and lower CO_2 emissions than OPC. However, one of the main issues with AAS is curing methodology. Previous studies showed that sealed curing is the most effective curing methodology; however, it is not practical and harder to be applied on site, while curing in air significantly reduced the compressive strength of AAS. Based on the literature, the authors believe that a new curing regime that mixes both water and air curing might combine both practicality and efficiency over using one of the mentioned curing methods solely.

3. Experimental Investigation

The physical and mechanical properties of three groups of alkali-activated slag concrete mixtures, where each group has a different W/B ratio; 0.35, 0.40 and 0.45, which also represents three equivalent alkali-to-slag ratios of 0.45, 0.55 and 0.65, respectively. The Na_2O percentage equivalent for the three W/B ratios are 10%, 12% and 14%, respectively. Each group consists of two mixtures, each with a different slag content, 350 kg/m^3 and 400 kg/m^3, and cured under two different conditions are to be investigated. Concrete mix design of the mixtures and their Na_2O percentage can be found in Table 1. The activator to be used is a combination of waterglass and sodium hydroxide, where waterglass is the source of silicate and Na_2O, while NaOH is another source of Na_2O only. The activators are to be mixed together for two minutes prior to adding it to slag and the mixture. The slump cone test is to be performed on the fresh AAS concrete mixtures, to determine their workability. While the mechanical properties to be tested comprises from: compressive strength, split cylinder tensile strength, flexural strength and modulus of elasticity. Where, compressive strength analysis is divided into two parts: early-age compressive strength and compressive strength at normal ages.

The two curing methods used are sealed curing, and a new proposed curing method in which specimens are left in water until 3 days from casting, then left in air in normal laboratory conditions until each of the following testing days, this method was based on the finding from the literature [29].

In order to keep the W/B ratio fixed, increasing slag content was accompanied by increasing water content. This was by increasing both free water and alkalis used to keep the alkali-to-slag ratio fixed. Trial mixtures showed that the mixing regime should be by dry mixing components, then add the alkali activators and mix the mixture for 1 minute, then additional water is added immediately, and the mixture is mixed for another 2 minutes. This showed to be the best activating method, as other mixing methods or delay in supplying water would make the mixture harden before being poured and reduce handling of the mixture. Furthermore, it was also noticed that if the mixing process stops more than 15 minutes, the mixtures would start to harden and becomes harder to handle the concrete during pouring process.

3.1. Materials

Ground granulated blast furnace slag (GGBS) of Indian origin and locally available in the Egyptian market is to be used in this research work; its chemical composition is listed in Table 2. The bulk density of the used slag is 1150 kg/m^3, while its specific gravity is 2800 kg/m^3, with the Blaine fineness of 408.8 m^2/kg, and the percentage of the particles finer than 45 μm is 96%. The lost-on-ignition and insoluble residues were 0.50% and 1.40%, respectively. The alkali activators used were a combination of commercially available waterglass (sodium silicate hydrates), composed of 32.8% SiO_2, 17.2% Na_2O and 50% H_2O, and a sodium hydroxide solution with 50% concentration. The used sand is a natural sand which was sieved, washed and oven dried prior to the work. Its fineness modulus is 2.80 and composed of particles retained on sieve size 4.75 mm and below. The compacted volumetric weight of the sand used is 1640 kg/m^3, its loose volumetric weight is 1345 kg/m^3, while its specific gravity is 2520 kg/m^3.

Table 1 – Concrete mixtures proportions

Mixture	Slag	Sand	CourseAgg.	Water	NaOH	Waterglass	W/B Ratio	M_s	Na_2O (%)
	(kg/m^3)	(kg/m^3)	(kg/m^3)	(liter/m^3)	(kg/m^3)	(kg/m^3)			
350S35[*] 350A35[**]	350	650	1150	44	32	126	0.35	1.2	10
350S40 350A40	350	650	1150	44	39	154	0.40	1.2	12
350S45 350A45	350	650	1150	44	46	182	0.45	1.2	14
400S35 400A35	400	650	1150	50	36	144	0.35	1.2	10
400S40 400A40	400	650	1150	50	44	176	0.40	1.2	12
400S45 400A45	400	650	1150	50	52	208	0.45	1.2	14

[*] *S: Mixture cured by sealing*

[**] *A: Mixture cured by full immersion in water until day 3, then cured in air until testing days.*

Table 2 – Chemical composition of GGBS (Indian origin) (% by weight)

SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	S	MnO_2	TiO_2	LOI*
35.40	36.87	17.40	6.83	1.40	0.24	0.35	0.11	0.50

**LOI: Lost on Ignition*

Sieve analysis of sand used is represented in Fig. 1. Sieved sand lied between higher and lower limits given by the ASTM C33/C33M-13 [30]. The used coarse aggregate is crushed dolomite of size 1 (Nominal maximum aggregate size of 10 mm).

In order to calculate Na_2O in liquid NaOH, the solution is multiplied by its concentration, which is 50%, then by 0.775, which is the amount of Na_2O in the solution in grams. While for sodium silicate, the Na_2O is calculated by multiplying the 17.2% percentage of Na_2O in the liquid sodium silicate by the weight of the used sodium silicate. While for SiO_2, it is calculated by multiplying the 32.8% of silicate by the amount of liquid sodium silicate used in each mixture. Dividing the SiO_2 by Na_2O produces the factor M_s which is silica modulus. The calculated M_s and Na_2O of each of the mixtures can be found in Table 1.

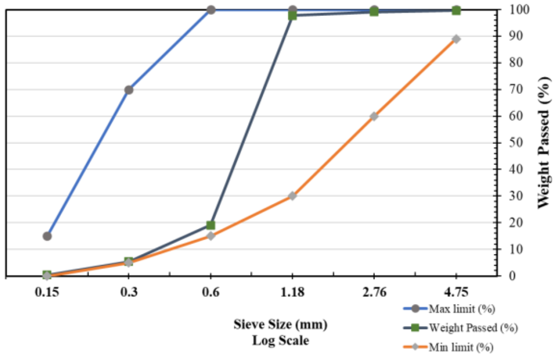


Fig. 1 – Sieve analysis of sand

3.2. Specimens

The mixtures were subdivided into three main groups using three different ratios of alkali activators of 0.45, 0.55 and 0.65 to the weight of slag used that yields water-to-binder W/B ratios of 0.35, 0.40, and 0.45, respectively. Calculating the W/B ratios was by multiplying the amounts of liquid NaOH and Na_2SiO_3 by the amount of water inside them; which is 50%, then the additional water, which is 12.5% by weight of slag, was added to the total, see Table 3. Each mixture in each group will have 36 cubes of size 100 mm x 100 mm x 100 mm for compression tests, 6 cylinders of size 100 mm x 200 mm for split cylinder tensile tests, 2 cylinders of the size 150 mm x 300 mm for modulus of elasticity tests, and 6 beams of size 100 mm x 100 mm x 500 mm for flexure tests. The 36 cubes will be divided into three groups, 12 for each. In the first group 12 cubes are to be for early-age compressive strength, in which each 3 cubes are to be tested at the age of 6, 12, 18 and 24 hours. While the second and third groups represent two different curing methods; but the specimens are to be tested at the same ages; which are: 3, 7, 28 and 91 days. The same is applied to the other specimens. The 6 small cylinders are to be divided into two groups, 3 cylinders per each curing method and tested at the age of 28 days under split cylinder tensile test. The 6 beams are also divided into two groups, 3 per each, and tested at 28 days under 4-point-beam-loading test. While the 2 big cylinders were tested for modulus of elasticity after 28 days, in which each cylinder represents a different curing method.

Table 3 – Calculation of water-to-binder ratio

Slag Content (kg)	Additional Water		Amounts of activators		NaOH				Waterglass			Total Water (kg)	W/B Ratio
	%	(liter)	%	(kg)	%	(kg)	Con.	Water (liter)	(kg)	Con.	Water (liter)		
350	12.5	44	45	158	0.2	32	50%	16	126	50%	63	123	0.35
350	12.5	44	55	193	0.2	39	50%	19	154	50%	77	140	0.40
350	12.5	44	65	228	0.2	46	50%	23	182	50%	91	158	0.45
400	12.5	50	45	180	0.2	36	50%	18	144	50%	72	140	0.35
400	12.5	50	55	220	0.2	44	50%	22	176	50%	88	160	0.40
400	12.5	50	65	260	0.2	52	50%	26	208	50%	104	180	0.45

(a) (b) (c)

Fig. 2 – Slump cone test of the mixtures (a) 350S35, (c) 350S40, (c) 350S45

3.3. Items of Investigation

Three water-to-binder ratios will be used where each ratio represents specific amounts of activators, which has a specific M_s and Na_2O. Two mixtures for each of the W/B ratios used are to be casted, where each of the two mixtures has a specific slag content. The slump of each of the mixtures is to be tested to determine the workability of each mixture. Each mixture will be cured by two methods; the first method is by sealing in polyethylene bags, while the other curing method is by full immersion in water until the age of 3 days, then taken out from curing tank and left in air in moderate laboratory conditions. The specimens are to be tested in compression at two stages: the early age stage where the specimens are tested at the ages of 6, 12, 18 and 24 hours, and the later ages stage where the specimens will be tested at the age of 3, 7, 28 and 91 days. Furthermore, the mixtures are tested at the age of 28 days using split cylinder test, flexure test, and modulus of elasticity test.

4. Experimental Results and Discussion

4.1. Slump Cone Test

The slump cone test was performed on fresh AAS concrete. Fig. 2 – (a), Fig. 2 – (b), Fig. 2 – (c), represent the slump cone of the mixtures with W/B ratio of 0.35, 0.40 and 0.45, respectively, for the mixtures with slag content of 350 kg/m^3. The results of the test are represented in Fig. 3. The results show that for the first group, the 350 kg/m^3 of slag mixture showed a zero mm slump, which mean that the mixture is very dry. Increasing slag content in the mixture to 400 kg/m^3 showed an increase in workability and slump to 20 mm. As for the second group, the slump cone was 20 and 98 mm, for the 350 and the 400 kg/m^3 of slag mixtures, respectively. As for the third mixture, increasing slag content of the mixture from 350 kg/m^3 to 400 kg/m^3, showed an increase in slump failure from 98 mm to 175 mm.

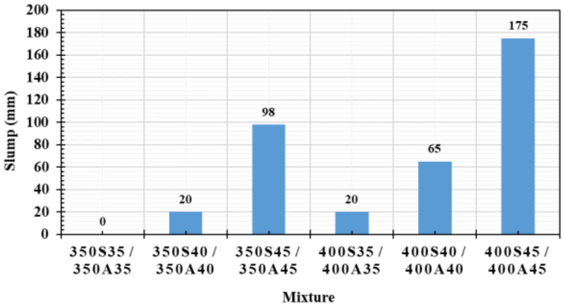


Fig. 3 – Slump cone test results of the mixtures

Although increasing slag content, which is increasing the bonding material in the mixture, should make the mixture drier; however, the increase of slag content is accompanied by an increase in the amounts of the activators and the additional water. Increasing the amounts of the activators and additional water in the mixture increases the amount of water in the mixture, which mean increasing the amount of water-per-cubic-meter. The amount of water in a cubic meter of the mixture should be regarded as a new and a major factor in determining the workability and slump of the mixture, see Fig. 4. In fact, increasing the water content of the mixture caused a slump increase of 20 mm for the first group, 45 mm for the second group, and an increase of 77 mm for the third group. This increase in the slump was due to an increase of 17, 20 and 22 litres/m^3 of water for the first, second and third groups, respectively.

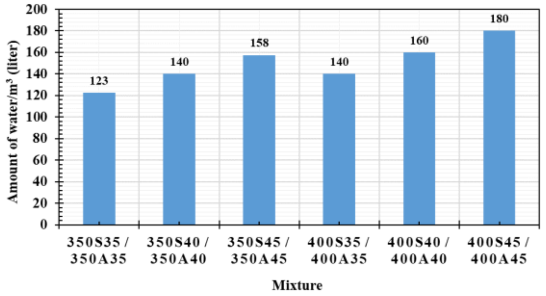
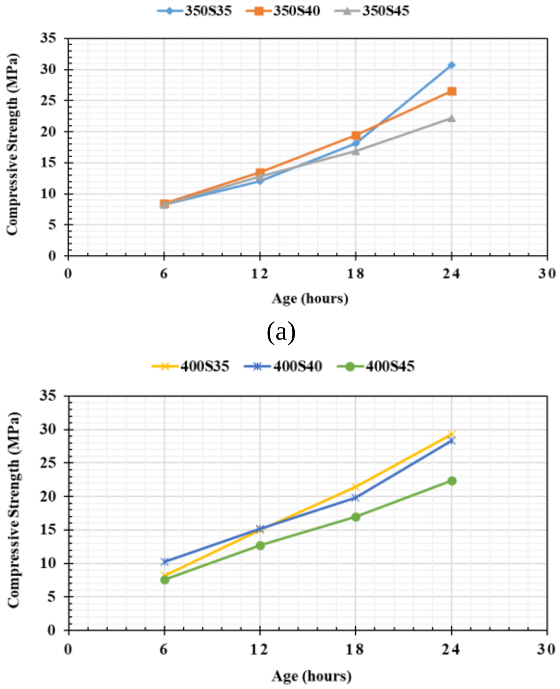


Fig. 4 – Water content of the mixtures

4.2. Early Age Compressive Strength

Compressive strength of AAS concrete mixtures at early age are represented in Fig. 5, for the 350 kg/m^3 and 400 kg/m^3 mixtures, respectively. The results show that at 6 hours, mixtures with slag content of 350 kg/m^3 had compressive strengths ranging from 8.3 to 8.5 MPa. On the other hand, mixtures with 400 kg/m^3 slag content mixtures, showed a compressive strength ranging from 7.6 to 10.3 MPa. The scheme of the curve in the second direction (comparing W/B ratio with compressive strength), see Fig. 6 seems to be like a parabola opened downwards; where the highest value is at W/B ratio = 0.40, while the other two ratios had a lower compressive strength. This phenomenon could be attributed to the literature which showed that the mixtures with low water-to-binder ratio, W/B = 0.35, was too dry and showed a lower workability, which had an effect on the compaction and the percentage of voids inside the mixture. While increasing the water-to-binder ratio to 0.40, increased both workability and compactness of the cubes; therefore, the compressive strength of the cubes increased. On the other hand, a further increase of the water-to-binder ratio to 0.45, showed an inverse effect where the compressive strength of the mixtures decreased again. This decrease could be attributed to that the specimens had higher amounts of water which caused them require a longer time to solidify, although they were more compacted. This can be noticed when unmolding the specimens at testing time. Furthermore, the increase in the W/B ratio was accompanied by an increase in Na_2O percentage, which is believed to increase shrinkage and stresses inside the specimens. Although, the compressive strength of mixtures with W/B ratios of 0.35 and 0.45, and slag content of 350 kg/m^3 were insignificantly higher than that of 400 kg/m^3; however, the mixture with W/B ratio = 0.40 showed an increase in compressive strength with increasing slag content from 350 kg/m^3 to 400 kg/m^3.



(a)

(b)

Fig. 5 . Compressive strength results of the mixtures at early age for slag content of (a) 350 kg/m^3, (b) 400 kg/m^3

At 12 hours, the scheme of the compressive strength of the mixtures was almost the same as the mixtures at 6 hours, except that the compressive strength of the mixture with W/B ratio = 0.45 and slag content of 400 kg/m^3 showed a significantly lower compressive strength than all the two other mixtures with the same slag content but with lower W/B ratio. The compressive strength at this age ranged between 12.1 and 13.5 MPa for mixtures with slag content of 350 kg/m^3. While it ranged from 12.7 and 15.1 MPa for slag content of 400 kg/m^3.

At 18 hours, the compressive strength of the mixtures increased, but the rate of increase for the mixtures with slag content of 350 kg/m^3 is increased over the higher slag content. However, the scheme of the curve changes for the higher slag content where the highest compressive strength was for the mixture with W/B ratio of 0.35 instead of the mixture with W/B ratio of 0.40.

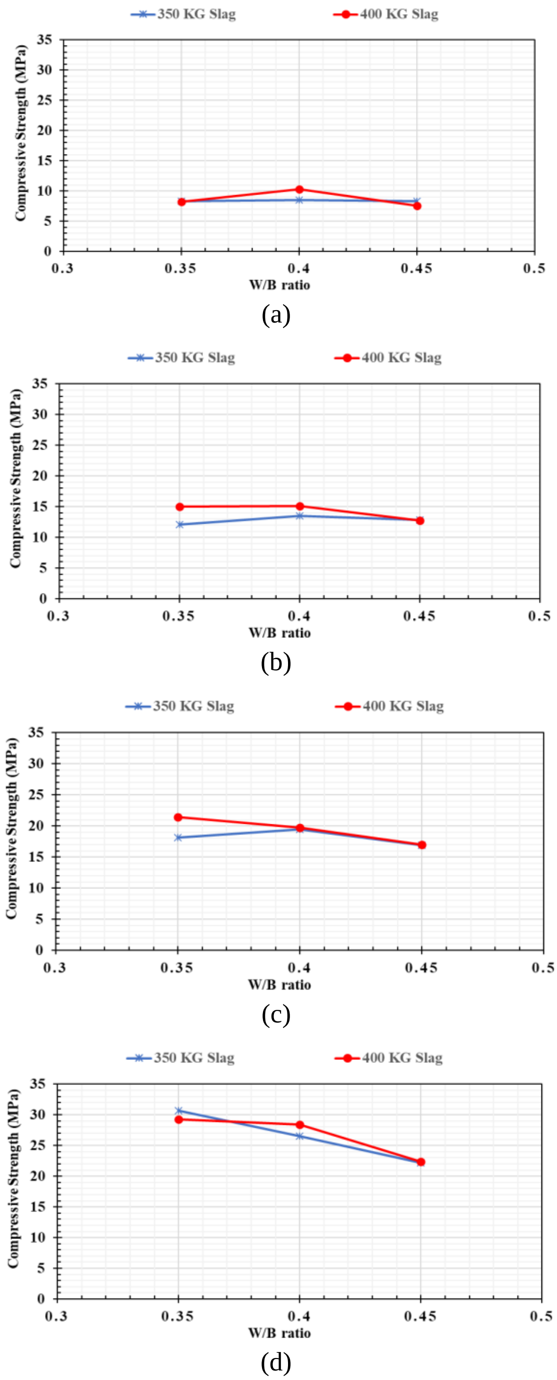


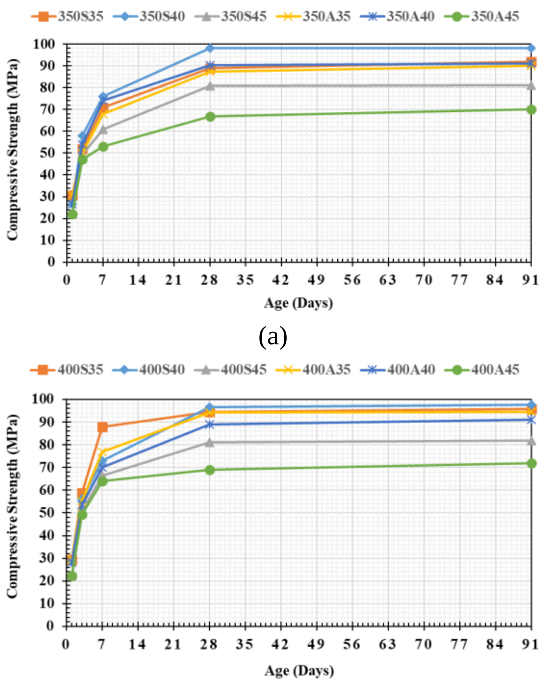
Fig. 6 – Compressive strength results compared to W/B ratio at the age of (a) 6 hours (b) 12 hours (c) 18 hours (d) 24 hours

On the other hand, the compressive strength at 24 hours increased significantly, where the compressive strength ranged between 22.2 to 30.7 MPa. At this age, the highest compressive strength became the mixtures with W/B ratio of 0.35, followed by the mixtures with W/B ratio of 0.40, followed by the mixtures with ratio of 0.45. Where the rate of increase of compressive strength of the mixtures with a W/B ratio of 0.35 was much higher than the other mixtures with higher ratios. This could be attributed to the fact that these mixtures had Na_2O percentage lower than the mixtures with a W/B ratio of 0.40 and 0.45.

The increase of the W/B ratio from 0.35 to 0.40 caused a reduction in compressive strength at 24 hours; although it showed an increase in strength at earlier ages, followed by a reduction in strength when the ratio increased from 0.40 to 0.45. Furthermore, the increase of the water-to-binder ratio represents an increase in the alkalinity of the mixture and Na_2O percentage, which in turns increase shrinkage and increase stresses inside the specimens. On the other hand, increasing slag content, the mixture, did not show a significant influence on the strength of the mixtures, neither at 6 hours, nor at 24 hours.

4.3. Compressive Strength

In the second stage of testing AAS concrete mixtures under compression, the specimens have been tested on ages 3, 7, 21 and 91 days. Furthermore, in order to broaden the range of study, the age of 24 hours (1 day) is used. The compressive strength results of the AAS concrete mixtures at mentioned ages are represented in Fig. 7. Failure mode of all the mixtures with slag content of 350 kg/m^3 is represented in Fig. 8. In general, the compressive strength of sealed specimens of all the mixtures were higher than the specimens cured by the newly proposed method. However, the difference in compressive strength between them was relatively insignificant at 3 days, where the difference did not reach 7% at maximum. On the other ages, the difference between sealed specimens and specimens cured by the new curing method was around 13%, 17% and 18%, for the age of 7, 28 and 91 days, respectively. This means that with the increase of the age the difference increased to be almost 18% at the age of 91 days. This is due to the high evaporation of liquids in specimens left in air and the shrinkage that might have occurred due to the dry surface. Furthermore, although increasing slag content from 350 kg/m^3 to 400 kg/m^3 should have increased the compressive strength; however, the compressive strength was significantly higher for mixtures with W/B ratio of 0.35. On the other hand, the increase in strength of the other mixtures with higher W/B ratios was relatively insignificant. This could be because increasing slag content added to the binding material but did not add to the overall strength of the mixture itself.

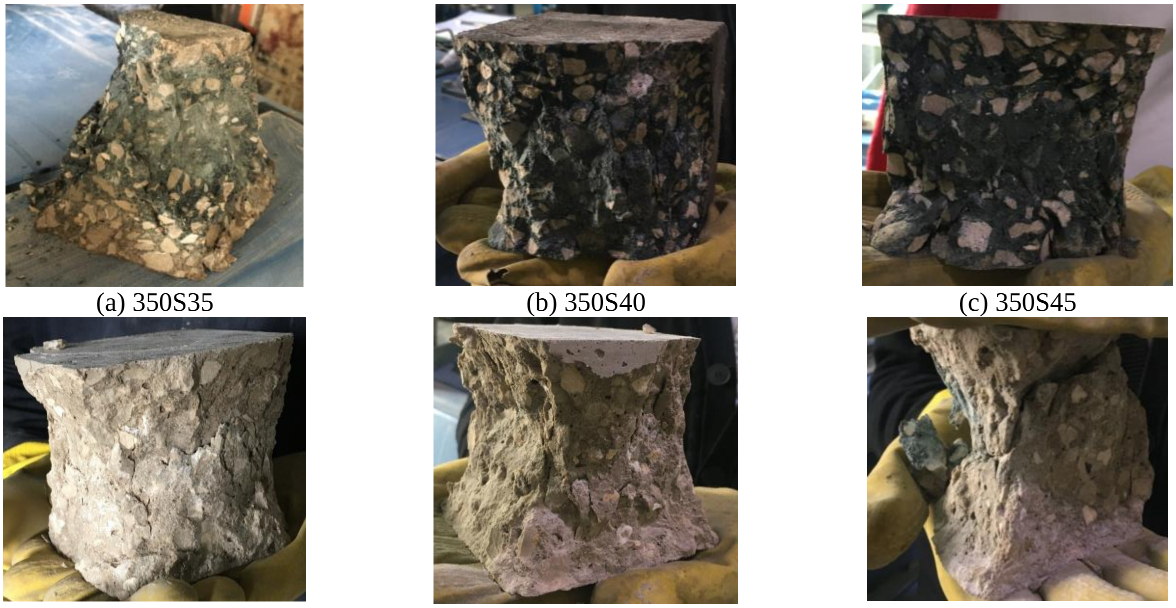


(a)

(b)

Fig. 7 – Compressive strength results of the mixtures for slag content of (a) 350 kg/m^3 (b) 400 kg/m^3

For slag content of 350 kg/m^3, and by comparing mixtures of the same curing type, mixtures showed a constant pattern where the compressive strength of the mixtures with a W/B ratio = 0.40 showed the highest compressive strength, followed by the mixtures of W/B ratio = 0.35, then finally the mixtures with a W/B ratio of 0.45. On the other hand, the mixtures with slag content of 400 kg/m^3 showed a different patter until the age of 7 days, where the mixtures with a W/B ratio = 0.35 showed the highest compressive strength, followed by the mixtures of W/B ratio = 0.40 and 0.45, respectively. However, the 28-day and 91-day compressive strength of the mixtures with a W/B ratio = 0.40 was the highest followed by the mixtures with W/B ratio = 0.35 and 0.45, respectively. The reason for this order could be due to that the mixtures with W/B ratio of 0.35 have Na_2O percentage of 10% which is lower than the other two mixtures, which is although its increase is believed to cause an increase in strength; however, there is a limit above which can cause higher shrinkage. While for the mixture with a W/B ratio = 0.40, which has a higher Na_2O percentage, Na_2O = 12%, it showed a higher compressive strength.



(a) 350S35 (b) 350S40 (c) 350S45

(d) 350A35 (e) 350A40 (f) 350A45

Fig. 8 – Failure mode of concrete cubes at the age of 28 days for the mixtures

This could be due to higher amounts of the activators and liquids, and improved workability; which caused a better compaction and allowed for an acceleration of the activation process. On the other hand, as for the third mixture with Na_2O percentage of 14%, and a W/B ratio of 0.45, the compressive strength is believed to be the lowest due to the highest Na_2O percentage, the higher amount of liquids which cause a replacement of other materials in the specimen, and cause a higher shrinkage due to the higher amounts of voids and the higher rate of evaporation which results in a higher shrinkage and damage to specimens microstructurally.

The highest compressive strength of mixtures with slag content of 350 kg/m^3 and 400 kg/m^3 at 91 days, for sealed mixtures is 98 MPa, for both contents, while for specimens cured with the new proposed method the strength is 91 MPa and 95 MPa, respectively. In fact, although sealed curing showed a higher compressive strength; but the benefit behind the new curing method and its applicability in the field, especially in mass concrete production for huge projects can overcome the benefit of the strength. Furthermore, although the increase in slag content did not increase the strength significantly in most of the mixtures; however, it caused a huge increase in the slump and the workability.

4.4. Indirect Tensile Strength

Split cylinder test was performed on AAS concrete cylindrical specimens of the size 100 mm x 200 mm. The results of the test are represented in Fig. 9. Sealed specimens showed a higher flexural strength than specimens cured by the new method; which is expected since the literature proved that sealed curing improves the mechanical properties of concrete specimens than the other curing methods [27]. This is due to keeping the humidity and reducing evaporation of liquids in the specimens, on the contrary of the other curing method, where the specimens are left in the air, where they are exposed to lose much more water by evaporation. However, the difference in the strengths between the specimens of each of the two curing methods and for each W/B ratio was relatively low. Furthermore, mixtures with slag content of 350 kg/m^3 showed a higher split cylinder tensile strength than the mixtures with the slag content of 400 kg/m^3. This could be attributed to that increasing slag content increased the amount of binding material, but it did not increase the overall strength of the mixtures, since the increase of slag content resulted in replacing part of the other materials in the specimens such as sand and coarse aggregate. Similar to compressive strength, the highest split cylinder tensile strength was that of the mixtures with W/B ratio of 0.40 for both slag contents. Nevertheless, the mixtures with W/B ratio of 0.35 showed the lowest indirect tensile strength. While the strength of the mixtures with a W/B ratio of 0.45 was in the middle between the other ratios, also for both slag contents. The low strength of the mixtures with a W/B ratio of 0.35 is believed to be due to lower compaction due to the lower slump, which resulted in greater voids inside the specimens which resulted in a reduction of adhesion of the specimen. This was obvious in the shape of the specimen itself and its surface which contained significant amounts of visible voids on the surface, see Fig. 10. On the other hand, the specimens with a W/B ratio of 0.45 showed higher strength than the latter due to the higher water content and slump which provided a much better compaction. However, the greater amount of water also affects the strength when the specimens dry is the microcracks and the internal voids initiated which also reduce adhesion in the specimens reducing the strength. That is why these mixtures showed a lower indirect tensile strength than the mixtures with W/B ratio of 0.40.

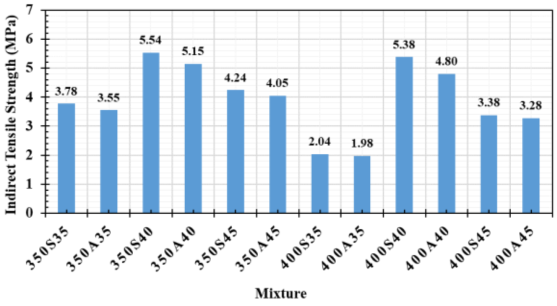


Fig. 9 – Split cylinder tensile strength test results for AAS concrete mixtures

4.5. Flexural Strength

In the beam flexure test, the trend of the strengths was similar to that of split cylinder tensile test, such that the highest flexural strength is of mixtures with W/B ratio of 0.40, followed by mixtures with W/B ratio = 0.45, and W/B ratio = 0.35, respectively, Fig. 11. Furthermore, mixtures with slag content of 350 kg/m^3 showed higher strengths than their equivalent mixtures with slag content of 400 kg/m^3. This can be also explained to be for the same reasons, where the increase of slag content did not affect the strength positively since it replaced some of the other concrete components in the specimens. While the specimens with the lowest W/B ratio showed the lowest flexural strength than the other two ratios are because of its low slump and compaction. While mixtures with a W/B ratio of 0.45 showed a higher strength, because of its higher compaction; yet, a lower strength than mixtures with a W/B ratio of 0.40, because of the higher amounts of water which evaporated and caused strength loss when evaporated.

(a) (b) (c)

Fig.10– Cylindrical specimens of split cylinder test (a) 350S35 (b) 350S40 (c) 350S45

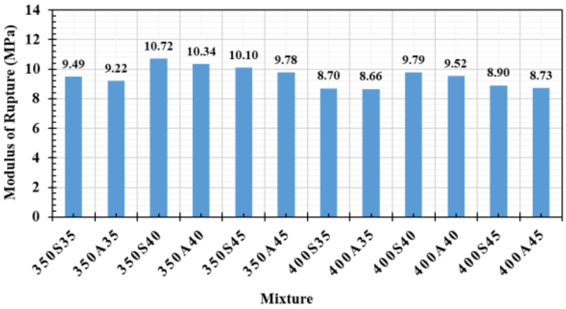


Fig.11– Flexural strength results of AAS concrete mixtures

4.6. Indirect Tensile Strength

Modulus of elasticity MOE of AAS concrete mixtures was measured on cylinders with the size 150 mm x 300 mm according to C469/C469M-10, 2010 [31] at 28 days. The results of the test are represented Fig. 12. The results show that elasticity modulus ranges between 30.5 GPa and 36.5 GPa for mixtures with slag content of 350 kg/m^3, and between 32.5 GPa and 37.5 GPa for mixtures with slag content of 400 kg/m^3. Increasing slag content increased modulus of elasticity of the mixtures, and it was noticed that it is higher for the sealed mixtures over the mixtures cured by the new suggested method, which both could be due to the higher water content in the mixtures. Furthermore, the highest modulus of elasticity was for the mixtures with W/B ratio of 0.40. While mixtures with a W/B ratio of 0.35 was lower in MOE, followed by mixtures with W/B ratio of 0.45. The increase and reduction of modulus of elasticity is very important in determination and expectation of compressive and tensile strengths of AAS concrete mixtures. The increase in modulus of elasticity is believed to represent an increase in the compressive and tensile strengths of the specimens, and vice versa. Which explains that the same trend of strengths in compression, tension and flexure, is almost the same as that of modulus of elasticity.

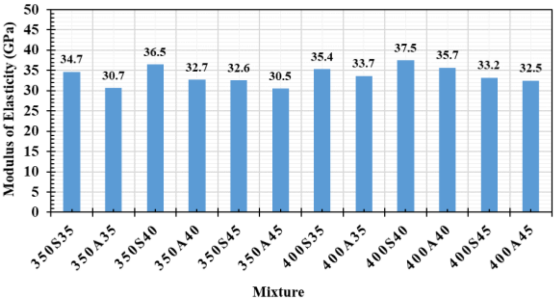


Fig. 12– Modulus of elasticity of AAS concrete mixtures

5. Further Research

It is suggested to intensively study this new curing methodology with different parameters. Furthermore, the usage of chemical admixtures to improve workability and slump of the mixtures should be investigated, to get both benefits of high strength and workability, which would be reflected on compaction. It is also suggested to use alkali-activated slag AAS concrete with Ordinary Portland cement OPC concrete of the same grade and strength and test the connection and bonding between them. This is to study whether AAS concrete could be used in retrofitting of old OPC concrete buildings.

Investigating the chemical resistibility and durability of AAS concrete is also of great importance.

6. Conclusion

Based on experimental investigation results, it was concluded the following:

1. Water-to-binder ratio is not the only measure for slump, increasing slag content for the same W/B ratio showed a significant increase in slump. This increase is due to the increase of water content in the mixture itself.
2. Increasing slag content from 350 kg/m^3 to 400 kg/m^3 showed an insignificant increase in compressive strength and modulus of elasticity. However, slump significantly increased, which in turns increased compaction of the specimens. This can be used for the goal of increasing workability not strength.
3. The new curing regime showed its effectiveness. Although strength of specimens cured by it was lower in strength than the specimens cured by sealing; however, the benefit of freedom to be used in mass projects and on-site instead of being only used as a precast concrete is beyond strength difference.
4. Increasing slag content showed a reduction in both split cylinder tensile strength and flexural strength for the same curing method and W/B ratio.
5. The strength of AAS concrete mixtures at early age reached up to 10 MPa and 31 MPa at the age of 6 hours and 24 hours, respectively. This means that formworks could be removed after only one day from pouring.
6. The compressive strength of AAS concrete mixtures reached up to 98 MPa at 28 days; however, at 91 days, no significant increase in strength was noticed. This high strength is very beneficial in projects where very high strength is required.

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