Journal of Marine Science and Technology

Volume 21 | Issue 3 Article 1

THE INFLUENCE OF MIXTURE VARIABLES FOR THE ALKALI-ACTIVATED SLAG CONCRETE ON THE PROPERTIES OF CONCRETE

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Acknowledgements

The authors want to express his thanks for the financial support from NSC, Taiwan under the grant numbers: 90-2211- E-019-017, 91-2211-E-019-020 and 92-2211-E-019-022

Journal of Marine Science and Technology, Vol. 21, No. 3, pp. 229-237 (2013)
DOI: 10.6119/JMST-012-0109-4

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Key words: alkali-activated slag concrete, slump, air content, unit weight, compressive strength, elastic modulus, splitting tensile strength.

ABSTRACT

In this study, the influence of three mixture variables named Sand/Aggregate ratio, Liquid/Binder ratio and Paste/Aggregate ratio on the concrete properties were studied. The properties of fresh concrete including the slump, air content and unit weight were examined. In addition, the mechanical properties such as the compressive strength, elastic modulus and splitting tensile strength were studied. Results showed that the alkali-activated slag concrete has superior strength. The 28-day compressive strength can reach 80% of the 90-day compressive strength. In addition, the influence of the Liquid/Binder ratio on the 28-day compressive strength is not as apparent as the water/cement ratio is for the ordinary Portland cement concrete. The trends of influences on the concrete properties for these three mixture variables are similar to those for the ordinary Portland cement concrete. It means that the experiences for making the ordinary Portland cement concrete should be able to be used for the alkali-activated slag concrete. This paper also provides substantial fresh-concrete and mechanical properties results for future development of the alkali-activated slag concrete mix design.

I. INTRODUCTION

The alkali-activated slag concrete (AASC) attracted lots of attentions recently and was thought as the construction materials for the next era [17]. Since the carbon dioxide is released during the manufacturing of the ordinary Portland cement, the ordinary Portland cement is considered as an environment-unfriendly construction materials nowadays. The alkali-activated slag concrete (AASC) on the contrary does not have much CO_2 emission then is thought as a rising star in the fields of construction materials [11]. Besides this, the AASC has the following superior properties: high compressive strength gain [14], good abrasion resistance, particularly when mixed with PTFE filler [18], excellent fire resistance than the ordinary Portland cement concrete [5, 9, 13], immobilization of hazard metals [10, 16], good resistance to acid attack [1], solidification of radioactive waste [15] and so on.

Although the development of AASC proceeded quickly in last decades, it has some problems which limited its application such as rapid setting [12] and higher amount of autogeneous and drying shrinkage [6]. Malic acid or sodium chloride [2] and phosphoric acid [3] have been reported to have good retarding effects. The gypsum [4] and polypropylenglycol derivatives can reduce the shrinkage. In addition, the AASC does not have a mix design procedure as the ordinary Portland cement concrete. In the reference, two mix design methods named as the empirical mix design method and the experimental design method are provided. The workability and strength development for AASC has been reported in [7, 8]. However, these data are not enough to build up a comprehensive understanding of the relationship between raw materials and concrete properties.

In this study, the influence of three parameters in mix design were examined and were named as the Liquid/Binder ratio (referred to the water/cement ratio of the ordinary Portland cement concrete), the Sand/Aggregate ratio and Paste/Aggregate ratio on AASC properties. The first focus of the test is the fresh concrete properties such as the workability, air content and unit weight; and the mechanical properties such as the compressive strength, elastic modulus and tensile splitting strength. The influence of such parameters on AASC durability will be reported in another paper. Through such a systematic research, the useful data can be provided for future development of mix design of AASC.

II. CONCEPTS OF THREE PARAMETERS

For the concrete, usually three phases can be distinguished: the binder, aggregates and the transition zone. The binder consists of water and the ordinary Portland cement for the

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ordinary Portland concrete (OPC) and it consists of the activator liquid and slag for AASC. The aggregates consist of the fine aggregates (size distribution less than #4 sieve size) and coarse aggregates (size distribution larger than #4 sieve size). The transition zone is the interface between the binder and aggregates. It is sometimes recognized as a thin layer or the weaker binder phase and thus is controlled by the properties of binder. In the OPC mix design, two approaches are mostly used nowadays.

The first approach follows the ACI design procedure which emphasizes the influence of water/cement ratio (Liquid/Binder ratio for AASC). From the idea of composite material, the properties of composite depend on the ratio between phases and their respective values. The binder in OPC is considered as the weakest phase in comparison with the aggregates. Therefore, in ACI design concept to control the properties of the weakest phase is the guideline of the whole design process. However, as the strength of binder increases such a design procedure might not be the optimal one.

The second approach emphasizes to minimize the Paste/Aggregate ratio by increasing the amount of aggregate. This idea comes from the physic concept that a denser composite owns a better strength property, i.e., a denser arrangement of raw materials makes a stronger composite. In this concept, we first fill a unit volume by aggregates as much as possible then fill the remaining voids by binder. However, to maximize the amount of aggregates usually result in poor workability such that some admixtures should be used to increase the workability.

Summarizing the abovementioned two approaches, two parameters are used. The water/cement ratio controls the properties of cement paste and the Paste/Aggregate ratio controls the amount ratio between binder and aggregates. Besides these two, there exists another ratio named Sand/Aggregate ratio, which describes the percentage of fine aggregates in whole aggregates, also affect the concrete properties. Although this ratio seems not so apparently influence the strength of concrete, it indeed affects workability and other properties when other parameters are fixed.

Following the experience of the ordinary Portland cement, we wonder what are the influences of these three parameters on AASC properties. In the OPC we know the water/cement ratio influence the strength apparently since the improvement of the weakest phase (paste) can enhance the strength dramatically. However, for the AASC the weakest phase is no longer the paste (paste can reach 12,000 psi compressive strength) but the fine aggregates (sand has lower compressive strength than paste and coarse aggregates due to wear and abrasion); then what influences do these three parameters make?

III. EXPERIMENTAL

1. Materials

The ballast furnace slag with specific surface of 4000 cm^2/g was used and its physical properties were listed in Table 1.

Table 1. The chemical and physical properties of slag.

The main chemical composition of slag (By weight percentage)	SiO_2 (%)	33.87
	Al_2O_3 (%)	14.42
	Fe_2O_3 (%)	0.69
	CaO (%)	39.54
	MgO (%)	5.35
	SO_3 (%)	2.47
	Basicity coefficient K_b = (CaO + MgO)/(SiO_2 + Al_2O_3)	0.93
Physical properties	Specific weight	2.90
	Ignition loss (%)	0.28
	Fineness (m^2/kg)	383

Crushed stones were used as the coarse aggregate and the fineness modulus was 6.40. The river sands were used as the fine aggregate and the fineness modulus was 2.59. The alkali activator was prepared by sodium hydroxide solution and sodium silicate ((SiO_2-37%, Na_2O-17.7%, H_2O-45.3%). To retard the fast setting behaviors of alkali-activated slag concrete, the phosphoric acid was used as a setting retarder. The alkali activator was mixed to keep the following proportion: SiO_2 = 100 g/l, Na_2O = 100 g/l, H_3PO_4 = 0.74 M. All specimens were made into the columns (ψ10 cm × 20 cm) and cured in the saturated lime water until test. In order to understand the influence of three parameters included Liquid/Binder ratio, Sand/Aggregate ratio and Paste/Aggregate ratio (where Liquid = alkali activator + phosphoric acid; Binder = slag; Aggregate = sand + coarse aggregate; Sand = fine aggregate (size less than #4 sieve size); Paste = liquid + binder.), a series of AASC were designed to examine the effects as shown in Table 2. It can be seen from Table 2 that for group I, we fixed the Liquid/Binder ratio (L/B) and Paste/Aggregate ratio (P/A) then examined the effects of Sand/Aggregate ratio (S/A). For group II, we mainly examined the effects of Liquid/Binder ratio. For group III, we mainly examined the effects of Paste/Aggregate ratio. The reason why we focus on the Sand/Aggregate ratio is because sands now become the weakest phase in comparison with paste and coarse aggregate and we expect this ratio might dominate concrete's properties just as the water/cement ratio does for the OPC.

2. Experiments Conducted

In this paper, the influence of three parameters on the fresh concrete properties and mechanical properties were examined. For fresh concrete properties, the slump test, air content and unit weight were studied. The slump test is a common test to examine the workability of concretes, which ensures the soundness during the placement of concrete. Air content test measured the air voids ratio produced by the entrance air during the mixing procedure. Generally speaking more air contents imply higher workability but lower compressive strength. The unit weight test shows the density of concrete which should be counted as the dead load. The concrete

Table 2. Mixture design.

	S/A	L/B	P/A	Air content (%)	Liquid (kg/m^3)	Binder (kg/m^3)	Fine aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)
I	**0**	**0.5**	**0.635**	**1.8**	285	570	0	1346
	0.2	**0.5**	**0.635**	**2.0**	284	568	268	1073
	0.4	**0.5**	**0.635**	**2.3**	283	566	534	802
	0.6	**0.5**	**0.635**	**2.4**	282	564	799	533
	0.8	**0.5**	**0.635**	**2.6**	281	562	1062	265
II	**0.2**	**0.4**	**0.635**	**2.5**	249	622	274	1098
	0.2	**0.5**	**0.635**	**2.0**	284	568	268	1073
	0.2	**0.6**	**0.635**	**1.5**	314	523	263	1054
	0.2	**0.7**	**0.635**	**1.2**	339	484	259	1036
	0.6	**0.4**	**0.635**	**2.8**	247	619	818	546
	0.6	**0.5**	**0.635**	**2.4**	282	564	799	533
	0.6	**0.6**	**0.635**	**1.9**	311	519	784	523
	0.6	**0.7**	**0.635**	**1.5**	336	481	772	515
III	**0.2**	**0.5**	**0.435**	**2.1**	230	459	317	1267
	0.2	**0.5**	**0.535**	**2.1**	259	518	290	1162
	0.2	**0.5**	**0.635**	**2.0**	284	568	268	1073
	0.2	**0.5**	**0.735**	**1.8**	306	612	250	998
	0.6	**0.5**	**0.435**	**2.7**	227	455	941	627
	0.6	**0.5**	**0.535**	**2.6**	257	514	864	576
	0.6	**0.5**	**0.635**	**2.4**	282	564	799	533
	0.6	**0.5**	**0.735**	**2.3**	303	607	743	495

material that has lower unit weight and higher strength can reduce cross-sectional area of structure members and thus save materials.

For the mechanical properties, the compressive strength, the elastic modulus and the splitting tensile test were studied. The compressive strength of concrete is the major design factor of reinforced concrete structures. Many design codes refer to the 28-day compressive strength since it is well known that 28 days make the maturity of concrete reaches above 80% for OPC and such that 28-day compressive strength can be viewed as the compressive strength of a mature concrete. In this study, we will examine that whether or not the AASC has the same feature as OPC. It means that whether or not the 28-day compressive strength is suitable to be taken as the compressive strength of a mature AASC. The elastic modulus is also important for the reinforced concrete structures. If the difference between elastic modulus for rebar and concrete is more significant, it results in poor consistence between two materials and develops larger mismatch strain when the volumetric deformation is constrained. It is known that the tensile strength of OPC is low since the interaction force between C-S-H gel is van der Waals forces. The main hydrated product is also C-S-H gel and the secondary hydrated products are similar to zeolite. The combination of these gels makes the AASC has different behavior in comparison with OPC. We will examine how the splitting tensile strength is and compare it to that of OPC.

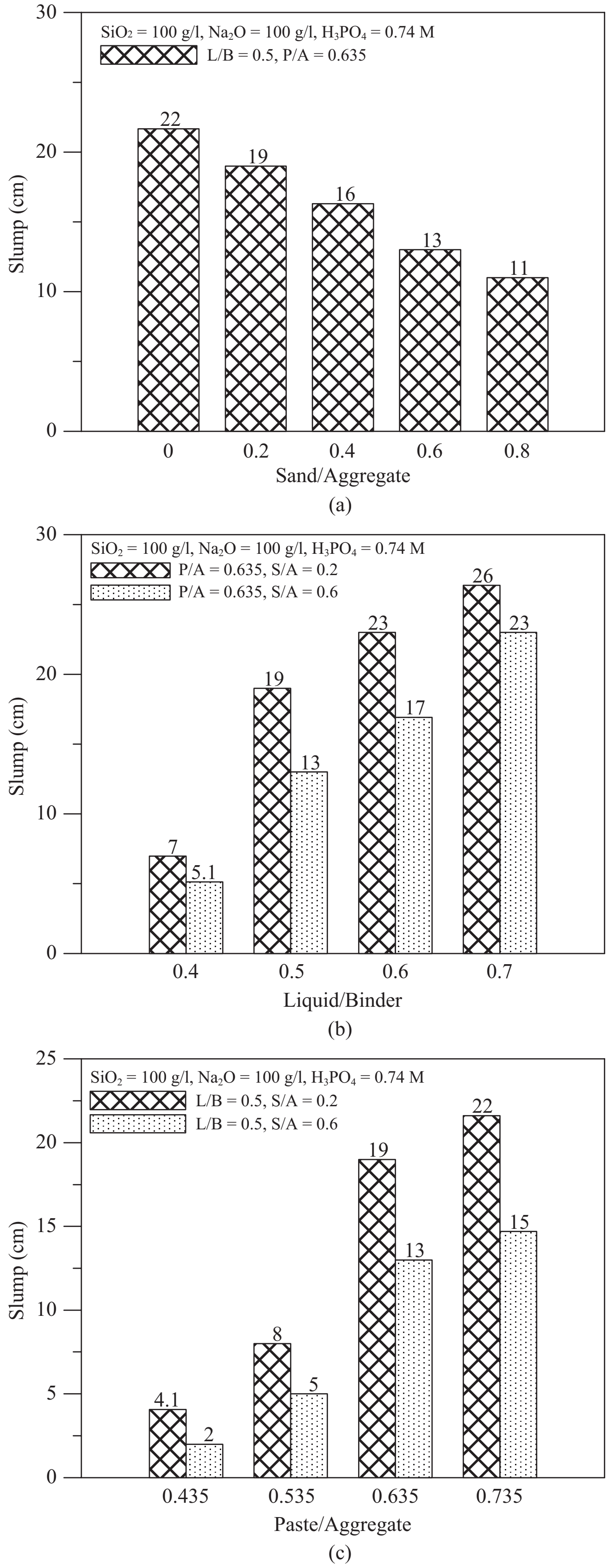


Fig. 1. The slump value (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

IV. RESULTS AND DISCUSSIONS

1. The Slump

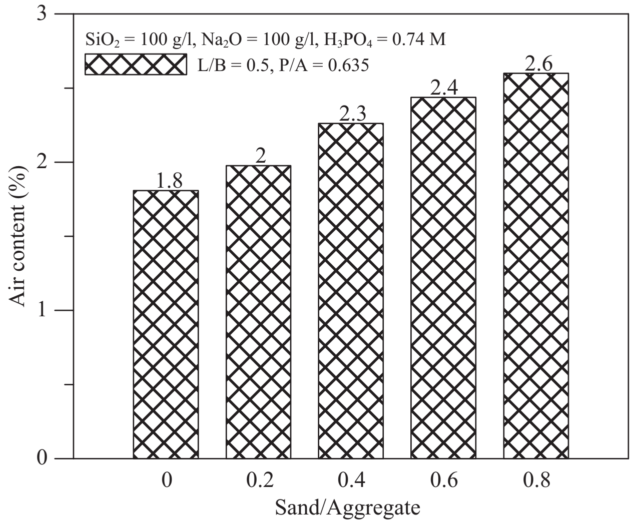
The influence of Sand/Aggregate ratio on the slump value is illustrated in Fig. 1(a). It can be seen as the Sand/Aggregate ratio increased, the slump value decreased. Increasing amount of sands implied that the specific surface of aggregates increased such that more paste was required to remain the workability. Therefore, as the Paste/Aggregate ratio kept as a constant the increment in Sand/Aggregate ratio then results in decrement of slump value. In Fig. 1(b), it can be seen that as the Liquid/Binder ratio increased the slump increased which is similar to the trend of OPC, i.e., increasing w/c ratio makes higher slump concrete. It is because that increasing Liquid/Binder ratio means higher amount of liquid is used and of course a higher workability is expected. In Fig. 1(c), it can be seen that as the Paste/Aggregate increased the slump value increased. It is because as the paste amount increased it would lubricate the interfaces between aggregates such that the workability became better. Overall speaking, the slump value is more sensitive to the changes of Liquid/Binder ratio and Paste/Aggregate ratio than the Sand/Aggregate ratio.

2. Air Content

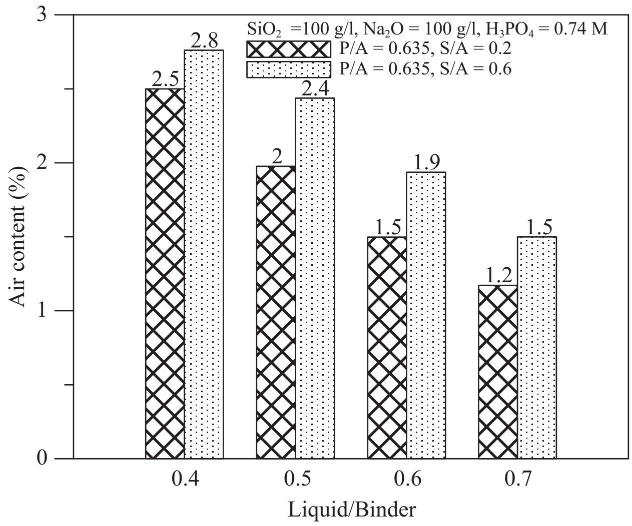
The air content increased as the Sand/Aggregate ratio increased as shown in Fig. 2(a). It is known that as the amount of sand increased, it generally introduced more entrained air during mix procedure. As the Liquid/Binder ratio increased, the air content decreased as shown in Fig. 2(b). It is because that as the Liquid/Binder ratio increased a concrete with higher workability we had and it then squeezed out air as the concrete flowed. In Fig. 2(c), it can be seen that as the Paste/Aggregate ratio decreased the air content increased. It also can be explained by the workability of concrete. As the Paste/Aggregate ratio decreased the slump value decreased, and the lower value of slump meant the entrained air had a lower possibility to be squeezed out from the mix when fresh concrete was placed. Generally speaking, the higher slump value of concrete we had the lower air content we had then.

3. Unit Weight

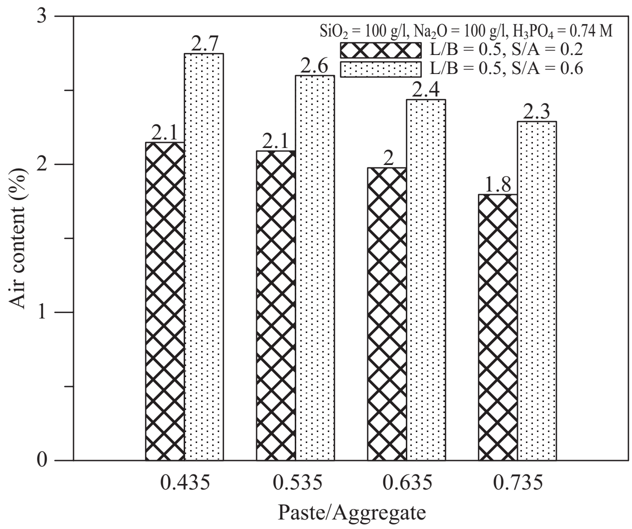
It can be seen that the change of Sand/Aggregate ratio almost did not affect the unit weight as shown in Fig. 3(a). It is because that the specific weights of fine aggregate (sand) and coarse aggregate are very close. Therefore, if we replace part of coarse aggregates by sands the unit weight does not vary much. In Fig. 3(b), it can be found that the unit weight decreased as the Liquid/Binder ratio increased. The alkali activator had a lower density than binder (slag) such that increasing the Liquid/Binder ratio results in a decrement in unit weight, and this trend is similar to that of OPC. In Fig. 3(c), it can be seen that as the Paste/Aggregate ratio increased, the unit weight decreased. The density of paste is lower than that of aggregates such that increasing the Paste/Aggregate ratio results in decrement in unit weight.



(a)



(b)



(c)

Fig. 2. Air content (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

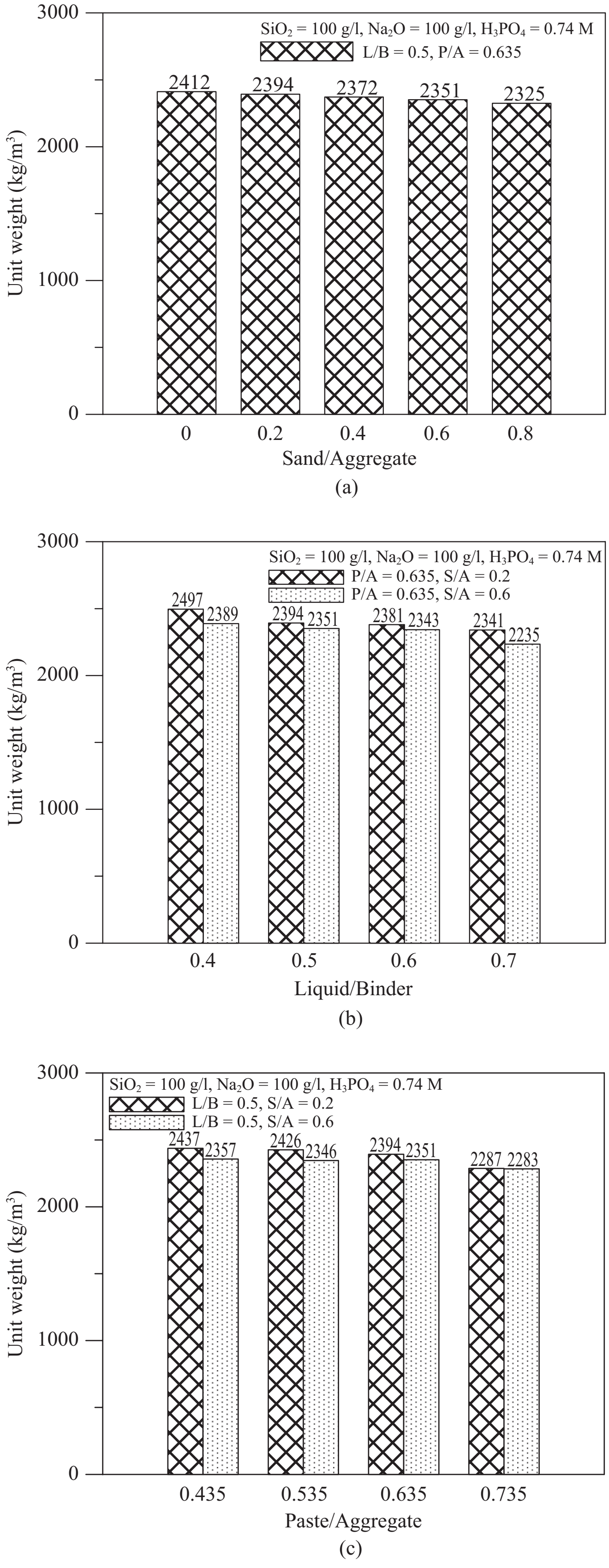


Fig. 3. Unit weight (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

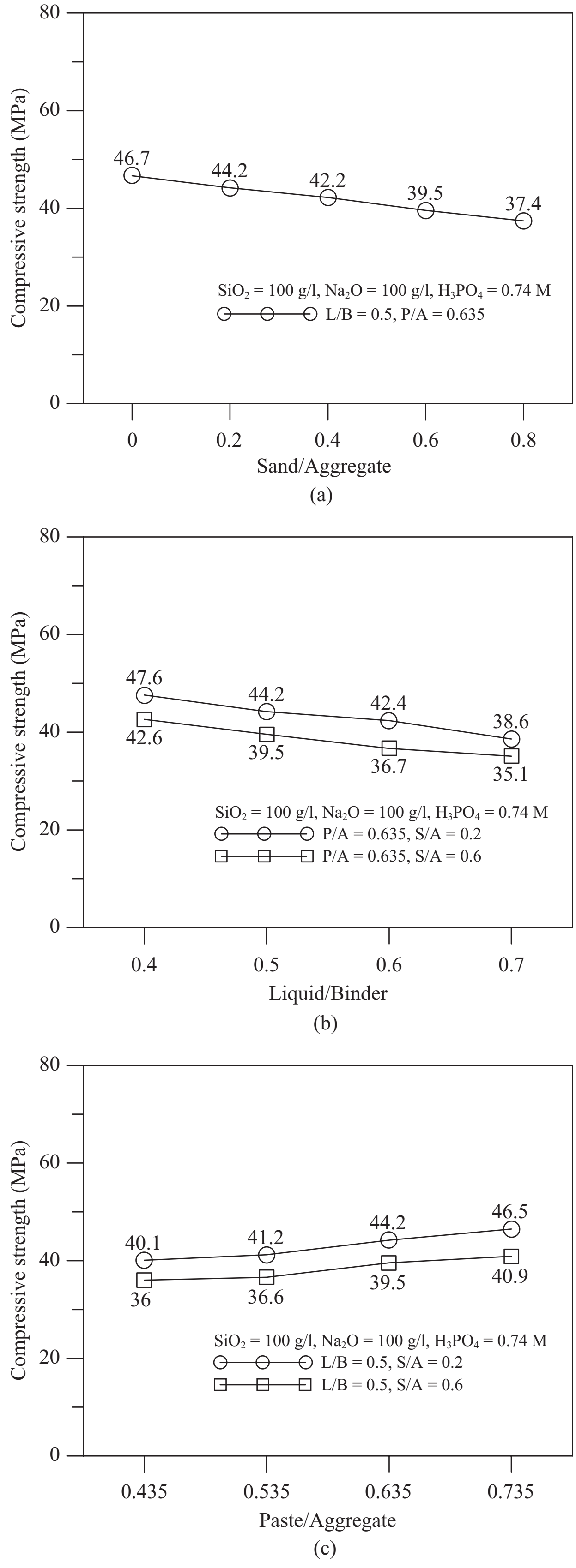


Fig. 4. Compressive strength (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

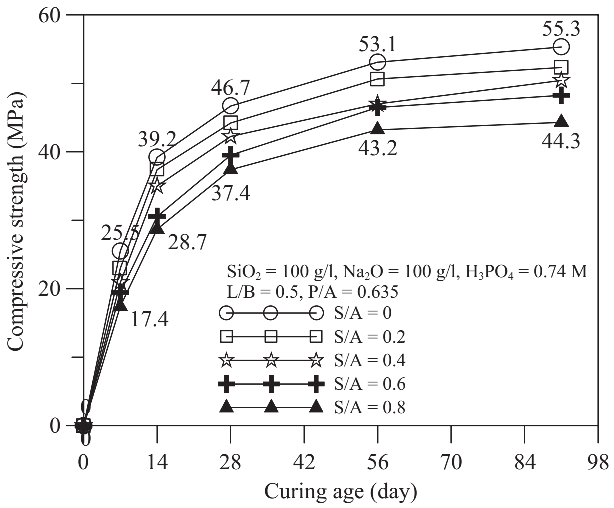


Fig. 5. The compressive strength developments of AASC.

4. Compressive Strength

In Fig. 4(a), it can be found that as the Sand/Aggregate ratio increased the 28-day compressive strength decreased. It can be understood because sand now is the weakest phase in the composite materials. In Fig. 4(b), it can be seen that as the Liquid/Binder ratio increased the 28-day compressive strength decreased. However, we should make a remark here that the 28-day compressive strength of AASC is less sensitive to the Liquid/Binder ratio than the 28-day compressive strength of OPC. Once again, this result shows that the role of w/c ratio is no longer the most dominant factor in AASC. In Fig. 4(c), it can be seen that as the Paste/Aggregate ratio increased the 28-day compressive strength increased. The paste in OPC is the weakest phase such that increasing amount of paste results in lower compressive strength. Therefore, for OPC we usually hope to fill most part of the volume by aggregates which results in a stronger concrete. However, for AASC this trend reverses then. The alkali-activated slag paste can reach a very high 28-day compressive strength such that it is no longer the weakest phase. In comparison with the integrality of aggregates (sands and stones), the paste becomes a stronger phase such that increasing amount of it results in a higher compressive strength. It should be noticed that in this figure the Sand/Aggregate ratios were 0.2 and 0.6. If the Sand/Aggregate ratio is 0, then the trend may be different depending on the compressive strengths of paste and coarse aggregates. From Fig. 4 and Fig. 3, we can say that although OPC and AASC have similar unit weight the AASC has a higher 28-day compressive strength than OPC generally. It means that the strength gain per unit mass material of AASC is more than that of OPC. It can be concluded that AASC is a better material than OPC.

In Fig. 5, the compressive strength developments of AASC with various Sand/Aggregate ratios versus age are illustrated. It can be found that for all of them, the 28-day compressive strength reach 80% of 91-day compressive strength which can be taken as the ultimate strength. This trend is similar with

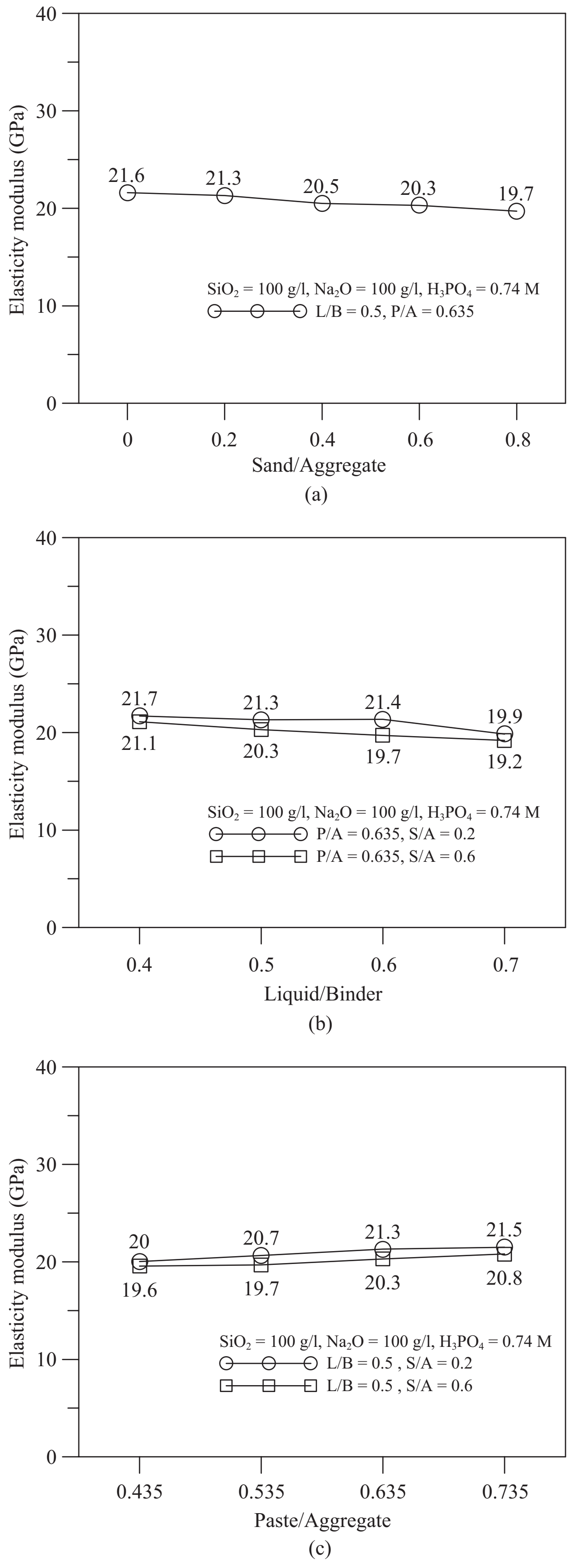


Fig. 6. Elastic modulus (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

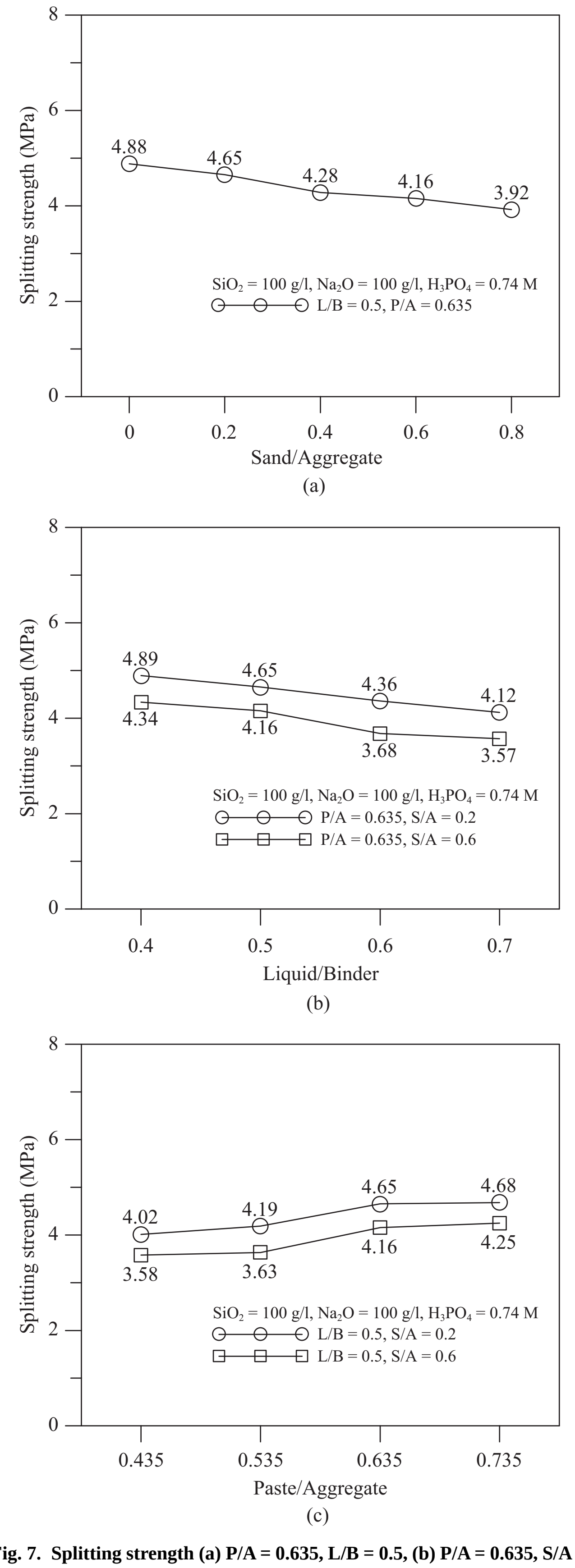


Fig. 7. Splitting strength (a) P/A = 0.635, L/B = 0.5, (b) P/A = 0.635, S/A = 0.2 & 0.6, and (c) L/B = 0.5, S/A = 0.2 & 0.6.

that of OPC. It then can be said that 28-day compressive strength of AASC is suitable to be taken as a design variable of RC structures just as OPC does.

5. Elastic Modulus

The elastic modulus decreased as the Sand/Aggregate ratio and Liquid/Binder increased as shown in Figs. 6(a) and 6(b). As the Paste/Aggregate ratio increased, the elastic modulus also increased as shown in Fig. 6(c). The trends of elastic modulus are similar to the trends of compressive strength. Once more, we can tell that among three parameters the Liquid/Binder ratio is not the most dominant parameter. The elastic modulus of various AASC mixtures ranged from 19.2 to 21.7 GPa.

6. Splitting Strength

In Figs. 7(a) to 7(c), the influences of three parameters on the splitting tensile strength of AASC are illustrated. The trends of three parameters are similar to the trends for compressive strength and elastic modulus. That is the splitting strength increased as the Sand/Aggregate ratio decreased or the Liquid/Binder ratio decreased or Paste/Aggregate ratio increased. Roughly speaking, the splitting strength of AASC is 1/10 of the compressive strength of AASC which is very similar to the OPC.

7. General Comments

In Table 3, the trends of fresh concrete properties and mechanical properties for three parameters are summarized. From this table, one can see that some trends are similar to the OPC but some are not. For example, for OPC increasing Paste/Aggregate ratio results in lower mechanical strength but this trend reverses for AASC. In addition, from the data we obtained we find that some experiences in OPC may not be directly used in AASC. For example, in OPC we have a higher compressive strength if the unit weight is higher generally. However, for AASC we can have close unit weight but very different compressive strengths. These differences suggest further studies are necessary to understand behaviors of AASC.

In Fig. 8 and Fig. 9, the relationship between the elastic modulus and splitting strength with respect to the square root of 28-day compressive strength are plotted. It can be seen that roughly speaking they remain the linear relation which is similar to OPC stated in ACI publications.

V. CONCLUSIONS

In this paper, we investigate the influence of three parameters, Sand/Aggregate ratio, Liquid/Binder ratio and Paste/Aggregate ratio on the fresh concrete properties and mechanical properties of AASC. It can be concluded that the Liquid/Binder ratio no longer plays as the major factor affecting the compressive strength. Instead, the Sand/Aggregate ratio and Paste/Aggregate ratio are more important. For OPC,

Table 3. The comparison of fresh concrete properties and mechanical properties for three mix design parameters.

	fresh concrete properties			mechanical properties		
	The slump	Air content	Unit weight	Compressive strength	Elastic modulus	Splitting strength
increase Sand/Aggregate ratio	--	+	--	--	--	--
increase Liquid/Binder ratio	+	--	--	--	--	--
increase Paste/Aggregate ratio	+	--	--	+	+	+

+: increment --: reduction

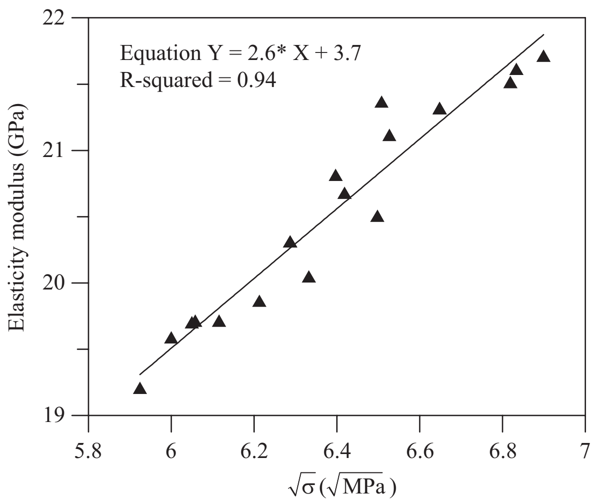


Fig. 8. The relation between elastic modulus and the square root of compression strength.

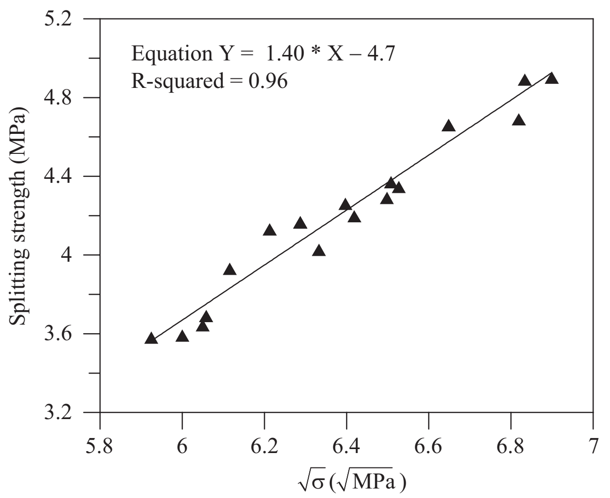


Fig. 9. The relation between splitting strength and the square root of compression strength.

increasing Paste/Aggregate ratio reduces the compressive strength. However, for AASC the trend reverses because the paste now is no longer the weakest phase. In addition, it was found that the elastic modulus and tensile splitting strength are linear function of the 28-day compressive strength which is similar to OPC. The unit weight of AASC is similar to OPC, but the compressive strength of AASC is higher than OPC. It means the strength gain per unit material mass is higher for AASC. The 28-day compressive strength of AASC reaches more than 80% of the mature value which is similar to OPC. Therefore, it can be concluded that 28-day compressive strength is suitable to be used as the design parameter for reinforced structure as that made of OPC. Most trends of three parameters on concrete properties are similar to those of OPC.

ACKNOWLEDGMENTS

The authors want to express his thanks for the financial support from NSC, Taiwan under the grant numbers: 90-2211-E-019-017, 91-2211-E-019-020 and 92-2211-E-019-022.

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