Jurnal Teknologi

Full paper

Physical and Mechanical Properties of High Performance Concrete with Alum Sludge as Partial Cement Replacement

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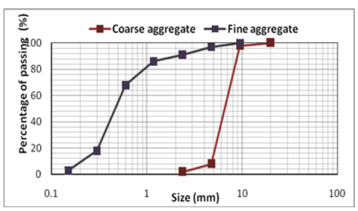
Article history

Received :20 August 2013
Received in revised form :
25 September 2013
Accepted :15 October 2013

Graphical abstract



Abstract

Alum sludge (AS) is a by-product of water treatment plants that use aluminum salts as a primary coagulant, and is the most widely generated water treatment residual/sludge worldwide. It usually contains colloidal alum hydroxides that are often amorphous species. The present paper examines the influence of AS powder as partial Portland cement type I replacement on the mechanical properties of high-performance concrete (HPC). AS with 90% fineness was passed through a 45 µm sieve (No. 325).The present study used a concrete mix with a fixed water/binder ratio of 0.33 and a constant total binder content of 483 kg/m^3.The percentages of the alum sludge by weight of cement were: 0%, 6%, 9%, 12%, and 15%. Slump tests were performed on fresh concrete to measure workability. The mechanical properties, dry densities, compressive strengths, and splitting tensile strengths of the concrete samples were investigated at 3, 7, and 28 days, whereas flexural strength was monitored at the age 28 days. Specimens without AS were compared with those that contained AS. The results revealed that the workability of the concrete consistently increased as the amount of cement replaced with AS increased. It was found that the concrete with 6% AS cement replacement demonstrated improved compressive strength and splitting tensile strength at all ages, compared with the control concrete.

Keywords: Alum sludge; high-performance concrete; workability; dry density; compressive strength; splitting tensile strength; flexural strength

■1.0 INTRODUCTION

The environmental friendliness of concrete cannot be fully appreciated without taking into account that the cement and concrete industries that provide ideal homes also generate enormous quantities of waste products from other industries. The cement and concrete industries are uniquely positioned to eliminate many wastes from the environment while receiving significant economic and technical benefits. The use of industrial by-products as replacements for natural materials is widely encouraged in construction, thus allowing residual materials to be recycled and valorized, while at the same time saving natural resources and energy. In cement production, residual materials can be used as substitute fuels, raw materials, and as supplementary cementing materials that replace part of the clinker. The treatment of drinking water to remove color, turbidity, and other impurities is steadily increasing. Water treatment plants annually produce about 80,000 tons of alum sludge waste as a by-product of the process of purifying water for human consumption.

The sludge generated in water treatment plants consists of organic and inorganic compounds in solid, liquid, and gaseous states, and varies in terms of physical, chemical, and biological characteristics (Bourgeois et al., 2004). The remaining volumes that are wasted depend on the characteristics of the operational units involved and the quality of the raw water. Chemical substances frequently used for water treatment include aluminum salts ($Al_2 (SO_4)3.18H_2O$), ferric ion salts (such as $FeCl_3.6H_2O$), and ferrous iron salts (such as $FeCl_2$, $FeSO_4.7H_2O$) (Fytianos et al., 1998). The addition of these chemical substances during water treatment may result in iron- or aluminum-rich sludge. These salts may be present in high concentrations that can be toxic to aquatic biota. To avoid this toxicity, the salts should be treated prior to disposal. Sludge from water treatment plants may also contain other heavy metals from raw water or from contaminants resulting from the addition of coagulants (Sotero-Santos et al., 2007). The aluminum hydroxide in water treatment sludge is insoluble and can be used as a coagulant in the primary treatment of sewage. The reuse of this sludge can improve the efficiency of primary sewage treatment and rationalize the treatment of water in sludge deposition (Guan et al., 2005).

Several trials of the use of water treatment sludge in various industrial and commercial manufacturing processes have been reported in Taiwan, UK, USA, Egypt, and other parts of the world. However, limited sludge disposal options have prompted interest in the reuse of sludge as an unconventional construction material. Studies were conducted to examine the potential of using sludge and sludge ash in the production of building and construction materials, as well as in brick, artificial aggregate, cement, and ceramics production. Typical examples of the direct use of sludge ash from wastewater treatment plants are: as filler in concrete (Tay, 1987), and as a cementitious building material (Tay and Show, 1992; Tay and Show, 1993). Nowadays, high-strength and high-performance concretes (HPC) are widely used throughout the world. Reducing the water/binder ratio and increasing the binder content are necessary to their production. Superplasticizers are used in these concretes to achieve the required workability. Various cement replacement materials are usually added to attain the desired low porosity and permeability. High-strength concrete was proposed and widely studied at the end of the last century. It is currently used in massive volumes due to its technical and economical advantages. Such materials, the so-called "21st century concrete," are distinguished by their enhanced mechanical and durability properties that result from the use of chemical and mineral admixtures as well as specialized production processes (Aitcin and Neville, 1993; Forster and Stephen, 1995; Zhongwei, 1998).

The main objective of this study is to explore on the physical and mechanical properties of high-performance concrete with alum sludge as cement partial .The use of this alum sludge may offer an effective means of recycling water treatment sludge, thereby helping reduce the environmental impact of the unregulated deposition of these wastes. When alum sludge can be used as pozzolanic material to produce high-performance, durable concrete, cement usage and the cost of high-performance concrete will be reduced and the . This technique will also benefit the environment by reducing the volume of waste disposed in landfills.

2.0 EXPERIMENTAL PROGRAM

2.1 Materials

2.1.1 Cement

The cement used in all concrete mixtures was ordinary Portland cement type I (OPC), which conforms to ASTM C150-1992. The physical properties and chemical compositions of this cement are stated in Table 1.

2.1.2 Aggregate

The fine and coarse aggregates were obtained from local sources in Malaysia. Local river sand with a fineness modulus of 2.37 was used as fine aggregate. Crushed granite with a maximum size of 10 mm was used as coarse aggregate. The particle size gradations obtained from the sieve analysis and the physical properties of the fine and coarse aggregates are presented in Table 2. The grading curves for the aggregates used shown in Figure 1.

Table 1 Chemical composition and physical properties of the cement

Chemical Analysis, (%)									**Bogue Composition, (%)**				**Physical Tests**	
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	LF	LOI	C_3S	C_2S	C_3A	C_4AF	Specific gravity	Fineness m^2/kg
67.17	20.99	4.60	4.44	2.53	2.98	0.03	0.91	0.63	68.10	9.16	4.69	13.50	3.12	328

Table 2 Sieve analysis and physical properties of the fine and coarse aggregates

Sieve size (mm)	**20**	**10**	**4.75**	**2.36**	**1.18**	**0.60**	**0.30**	**0.15**	**Fineness modulus**	**Relative S.G**	**Absorption (%)**	
Fine aggregate	--	100	97	91	86	68	18	3.0	2.37	2.61	0.78	
Coarse aggregate	100	98	8.0	2.0	---	---	---	---	----		2.57	0.48

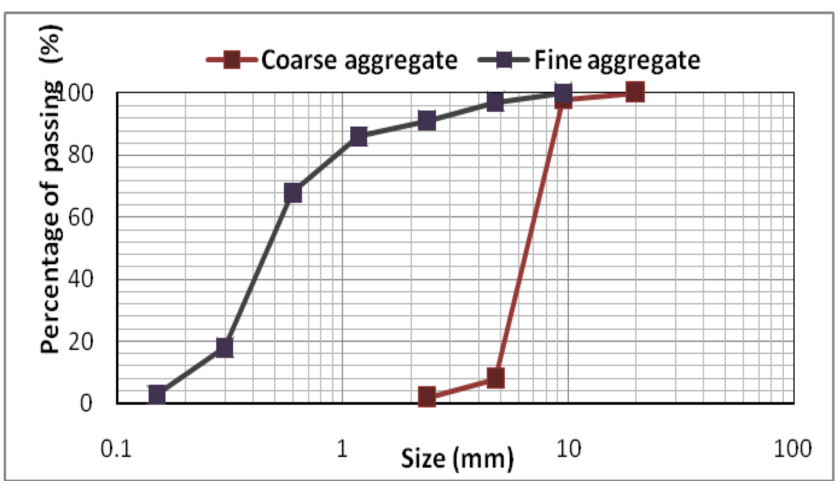


Figure 1 Grading curves of aggregates

2.1.3 Alum Sludge

The alum sludge (AS) powder is prepared before it is mixed with cement for the production of HPC. Figure 2 shows the schematic flow diagram of the preparation of the alum sludge sample. The AS was collected at ABASS Consortium water treatment plant and then oven-dried at 105 °C as in Figure 3, to a uniform dryness of at least 95% solid content to facilitate grinding. The dried sludge was crushed and screened through a 10 mm sieve to remove coarse and foreign particles (if any) from the material. The dried AS was then ground using a Los Angeles abrasion test (LAAT) machine until the required fineness was achieved (see Figure 4). The particle fineness of the ground mixture was ensured by using a 45 µm sieve ring mounted on the mill. The ashes obtained were ground to meet ASTM C 618-2003 fineness specifications.

The organic material content in the dried and ground sludge was determined through the loss on ignition (LOI) test, which is used to determine the organic matter content of oven-dried material by firing it in a muffle furnace at 440 ± 5 °C. The chemical composition of the sludge was determined using X-ray fluorescence (XRF) spectrometry. The complete chemical composition of the AS and its physical properties are summarized in Table 3. The main component of the AS was 42.38 % SiO_2. The total amount of SiO_2, Al_2O_3, and Fe_2O_3 was 82.35 %. Although alum sludge is not a natural pozzolan, it can be classified as a Class N (natural) pozzolan based on its chemical composition, which is the combined silica, alumina and iron oxides of more than 70% as specified by ASTM C 618.

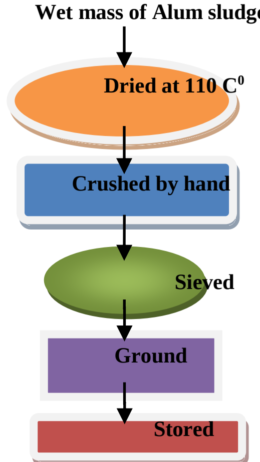


Figure 2 Schematic flow diagram of the preparation of the alum sludge sample

Figure 3 Alum sludge oven-dried at 110 °C

Table 3 Physical properties and chemical composition of the alum sludge

Chemical Analysis, (%)										Physical Tests	
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	LOI	Specific gravity	Moisture content (%)
42.38	35.03	4.94	0.13	0.29	0.14	0.10	1.87	0.26	11.86	2.34	0.85

Figure 4 Ground alum sludge

2.1.4 Superplasticizer

An aqueous solution of modified polycarboxylate-based superplasticizer (Viscocrete-2044) produced by Sika Kimia Sdn Bhd, Malaysia.

2.2 Concrete Mix Proportion and Preparation of the Samples

Alum sludge was used to partially replace the Portland cement at 6%, 9%, 12%, and 15% by weight of binder, as given in Table 4. The control mix was cast using OPC, whereas the other mixtures were prepared by replacing part of the cement with AS at four different replacement levels on a mass-for-mass basis. All mixture proportions had the same binder content of 483 kg/m^3. The water to binder (W/B) ratio was kept at 0.33, with the same amount of slump. A rotating pan mixer was used to mix the constituent materials. The concrete quantity was always prepared at 25% in excess of the required amount. The constituents were weighed in separate buckets.

The materials were mixed in a rotating pan, in accordance with ASTM C192-2002. Overall mixing time was about 5 min. The mixtures were compacted using a vibrating table. The slump of the fresh concrete was determined to ensure compliance with the design value and to study the effects of AS replacement on the workability of the concrete. The mixtures were cast as specimens using 100 mm x 100 mm standard cube moulds and 100 mm x 200 mm cylinders, and then covered to prevent loss of water due to evaporation. After casting, the molded specimens were left in the casting room at 23 ± 1.7 °C for 24 h, cured in a water tank, and then tested at room temperature at the required ages. To determine the compressive strength, twelve 100 mm x 100 mm x 100 mm cubes were cast for each mix, and three samples were tested after 3, 7, and 28 days of curing.

The splitting tensile strength test was performed on the 100 mm x 200 mm cylinders. Three samples were cast and tested after 3, 7 and 28 days of curing for each mix. Also, to determine the flexural strength for each mix, three 100 mm x 100mm x 500 mm prisms were cast and tested after 28- days of curing.

Table 4 Concrete mix proportions of the HPC mixtures.

Mix description %	W/B	Cement Kg/m^3	Alum sludge Kg/m^3	Fine aggregate Kg/m^3	Coarse aggregate Kg/m^3	FA / TA %	S.P (% by mass of OPC)
Control–OPC	0.33	483	0	656	1049	0.385	2.0
AS 6	0.33	454	29	656	1049	0.385	2.0
AS 9	0.33	439.5	43.5	656	1049	0.385	2.0
AS 12	0.33	425	58	656	1049	0.385	2.0
AS 15	0.33	410.5	72.5	656	1049	0.385	2.0

Note: FA- Fine aggregate, TA- Total aggregate, S.P- Superplasticizer

2.3 Test Procedures

2.3.1 Workability Test

The workability of the fresh concrete was measured through the slump test, in accordance with ASTM C143-2003.

2.3.2 Dry Density Test

The density of hardened concrete was determined by measuring the dimensions and weight of the cubes (100 mm x 100 mm x 100 mm) sample before crushing.

2.3.3 Compressive Strength Test

The compressive strength of the concrete was determined by crushing three 100 mm size cubes at ages 3, 7, and 28 days for each mix. The test was carried out according to B.S.1881 part 116:1983 using a compressive machine with capacity of 5,000 KN.

2.3.4 Splitting Tensile Strength Test

The splitting tensile strength was determined following the procedure outlined in ASTM 496/C 496M-2004. Cylinders (100 mm x 200 mm) were used.

2.3.5 Flexural Strength Test

This flexural strength test was carried out on (100 mm x 100 mm x 500 mm) prisms in accordance with ASTM C293-2002, using a simple beam with center-point loading.

■3.0 RESULTS AND DISCUSSION

3.1 Workability

After mixing, all mixtures were immediately tested using the slump test; the results are shown in Figure 5. The slump was in the range of 60 mm to 80 mm for the concrete control mixture. No segregation or bleeding was observed in the concrete with alum sludge. As shown in Figure 5, the workability had significantly increased as compared with the OPC concrete, and the workability increased with increasing AS proportion. Hence, the addition of AS reduced the water demands of the HPC, resulting in enhanced workability, because the water/binder ratio and the superplasticizer dosage were kept constant. This behavior is similar to the “ball-bearing effect” exhibited by fly ash due to its spherical shape and fine particle size distribution (Joshi and Lothia, 1997).

3.2 Density of the Concrete

Replacing ordinary Portland cement with AS reduced the density of the concrete. The densities of the samples in the study ranged from 2,403 kg/m^3 to 2,349 kg/m^3. The 15% AS mixture had the lowest density, because AS has a much lower specific gravity than cement, thus reducing the mass per unit volume. The concretes that used 15% alum sludge achieved approximately 2.5% density reduction, compared with the control HPC mixture, as shown in Figure 6.

3.3 Compressive Strength

The compressive strengths of the HPC containing various proportions of AS and the effects of replacing cement with AS in concrete are shown in Figure 7. Significant improvement was observed in the strength of the HPC with 6% cement replacement by alum sludge (AS6) across all ages, compared with the control concrete. The improvements were 3.4%, 5.5%, and 7% increases on days 3, 7, and 28, respectively. The compressive strength of the concrete sample with 6% AS was higher than those of the samples with 9%, 12%, and 15% AS in the early and later ages. Part of the reason is that the higher Portland cement Type I content (94%) in the 6% AS induced more hydration reactions than in the 9%, 12%, and 15% AS concretes. The compressive strength and rate of hydration were also higher in the 6% AS than in the control concrete, because of alum sludge’s pozzolanic properties. This result could also be due to the sludge’s fine particle size and its reaction with dioxide silicate in the form of an amorphous structure.

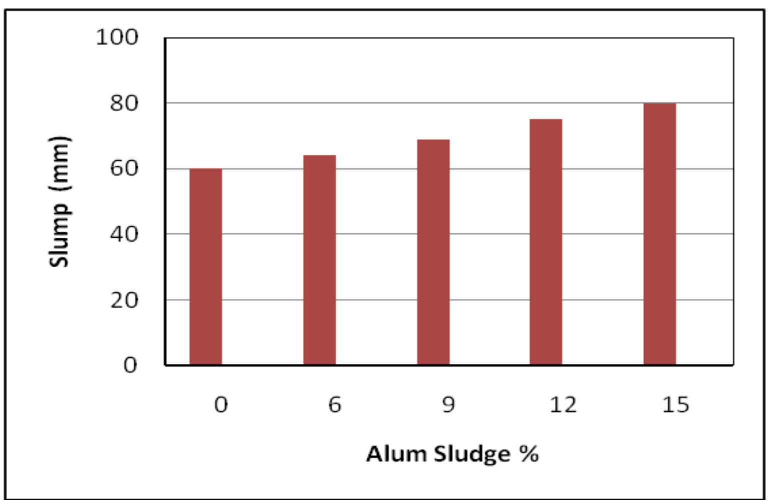


Figure 5 Effect of alum sludge on the slump

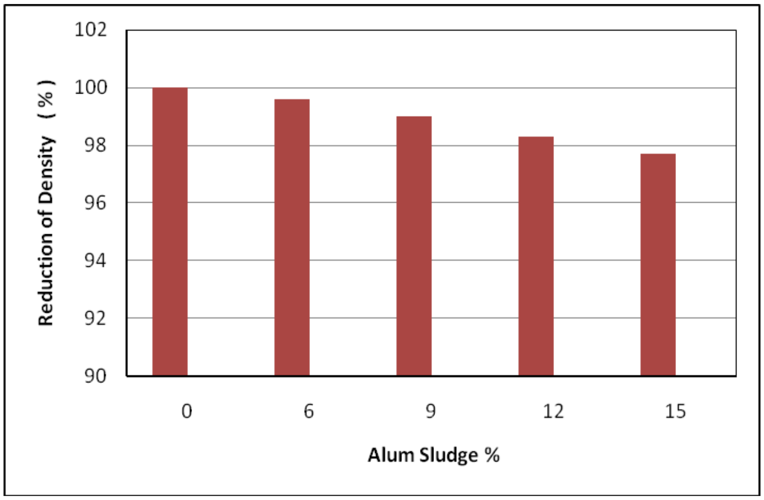


Figure 6 Effect of alum sludge on the reduction the density

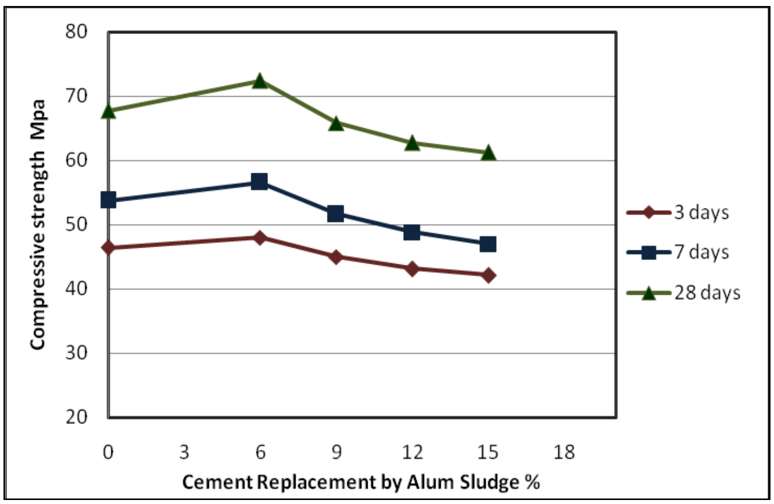


Figure 7 The effect of AS on compressive strength

3.4 Splitting Tensile Strength

Tensile strength tests were carried out at sample ages 3, 7, and 28 day. The test results for the HPC across all mixtures are presented in Figure 8. Through the Figure 8 shows that the tensile strength of concrete behaved similarly to the compressive strength. The average tensile strength was within the permissible values, in accordance with design specifications. The results revealed that concrete containing 6% AS has greater splitting tensile strength than the control concrete across all ages. Beyond this replacement level, the tensile strength decreases. The ratio of splitting tensile strength to compressive strength at 28 days was between 6.7 % and 7.2 %, which is lower than the results obtained from normal- and medium-strength concrete, which range from about 8% to about 10%. This result indicates that as the compressive strength of concrete increases, the ratio of splitting tensile strength to compressive strength decreases, which is consistent with the results of other studies on high-strength concrete (Haque and Kayali, 1998; Shannag, 2000).

3.5 Flexural Strength

Flexural strength tests were carried out at sample at 28 day. Similar results with the splitting tensile strength, a significant increase in the flexural strength of the HPC with the 6% of cement replacement by alum sludge at 28 day, compared with the control concrete and this a similar manner to that of compressive strength as shown in Figure 9.

■4.0 CONCLUSION

From the results presented here of using alum sludge in Malaysia as pozzolans in high-performance concrete, the following conclusions may be drawn:

1- Alum sludge is a by-product of water treatment plants in Malaysia. Water treatment sludge may be used with cement in the development and production of HPC, and also in the production of building and construction materials in Malaysia. The results obtained in the present paper open new possibilities for future studies on mortar or concrete.
2- The alum sludge has a chemical composition similar to clay with the presence of silica and alumina. Although alum sludge is not a natural pozzolan, it can be classified as a Class N (natural) pozzolan based on its chemical composition, thus, it can be used as a pozzolanic material for cement replacement in concrete.

3- The workability of AS concrete mix increases as the replacement levels increases.
4- Density is observed to decrease as the partial replacement of cement with alum sludge increased.
5- The best of replacement proportion of AS from cement was 6%, compared by replacing 9%, 12% and 15% of cement.

The concrete with 6% alum sludge shows improved strength across all ages. On day 28, its compressive strength, splitting tensile strength and flexural strength were higher than those of the control sample by 7%, 4% and 4.7% respectively.

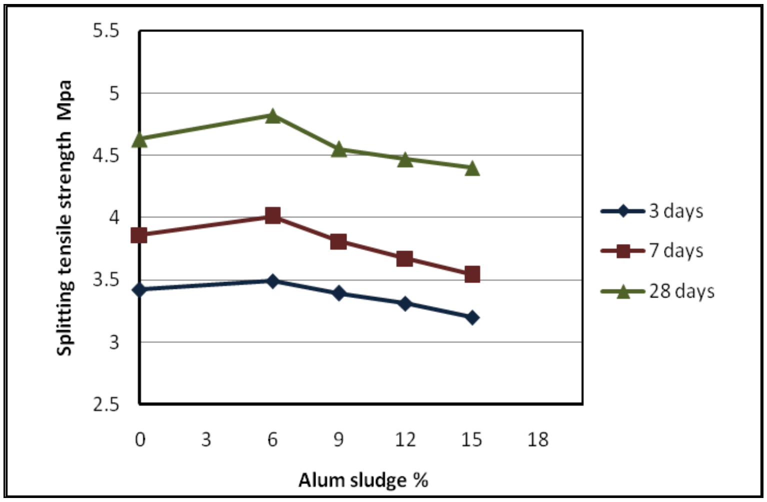


Figure 8 The effect of AS on splitting tensile strength

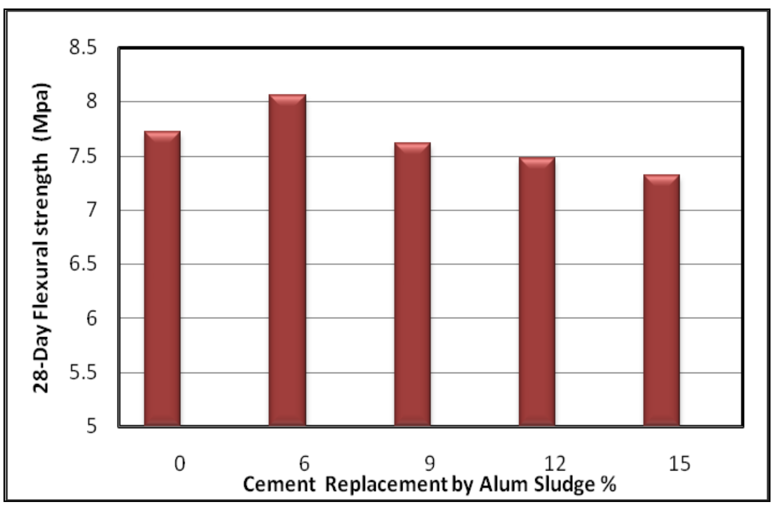


Figure 9 The effect of AS on flexural strength

Acknowledgements

The authors acknowledge the Ministry of Science, Technology and Innovation Malaysia for providing the financial support through project 06-01-02-SF0755. The authors also wish to thank the ABASS Consortium water treatment plant, Malaysia, for their cooperation in providing the alum sludge.

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