

EFFECTS OF STEAM CURING ON STRENGTH DEVELOPMENT OF SODIUM CARBONATE AND SODIUM SILICATE ACTIVATED FLY ASH/SLAG MORTAR

Cheah Chee Ban
School of Housing Building and Planning
University of Science Malaysia, 11800.Penang, Malaysia
Email: cheahcheeban@usm.my , Tel: +60 046532827

Tan Leng Ee (Corresponding Author)
School of Housing Building and Planning
University of Science Malaysia, 11800.Penang, Malaysia
Email: tanleengee3211@live.com , Tel: 016-4879692

ABSTRACT

To maintain the continuous growth of a nation, development in the construction industry is the most crucial in order to locate more residents, as well as creating more business opportunities. Previously, there are a few types of research discussed the impact of using traditional building material to the environment. The environmental effects can be estimated by considering the production of 1m³ of concrete, then summing up the potential environmental impacts of raw material used for the production of concrete. Thus, research on using geopolymer binders such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS) to replace cement are frequently done by several researchers. There are some limitations for geopolymer concrete, such as low early strength and long setting time. Furthermore, the use of a high amount of sodium silicate as an alkaline activator, in turn, makes the geopolymer concrete is creating another environmental problem instead of global warming. Sodium hydroxide is often used as alkaline activator, but the high pH of sodium hydroxide makes it hazardous in handling. To speed up the strength development of geopolymer, heat curing is normally used. However, heat curing by oven dry is not so favourable as increasing the oven temperature will increase the power of electricity. This would, in turn, use more electricity and the geopolymer is no more environmental friendly. Steam curing could achieve higher curing temperature as the steam from a continuously boiling water is often more than 100°C. In this study, PFA and GGBS are used together as the main binder. Sodium carbonate and sodium silicate are used as the alkaline activator. Steam curing is done at the age of 7 days and the strength is compared with samples with the age of 7 days and 28 days without steam curing.

Keywords: GGBS,PFA,Sodium Carbonate, Steam Curing

Introduction

The use of PFA not only could solve the pollution problem resulted in clinker process of Ordinary Portland Cement (OPC) but also enhance the strength of concrete, where High Strength Concrete can be obtained when PFA is incorporated[1]. More studies included PFA into cement because PFA increases the resistance towards acid attack and sulphate attack, contribute to strength enhancement at the later age and also contribute to fire resistance properties [2-5]. Fly ash could reduce the temperature rise during the hydration process of cement[6]. Fly ash has a low early strength due to it poses a weak pozzolanic property. The pozzolanic reaction is not initiated immediately after mixing [7, 8]. This could be overcome by curing fly ash concrete under elevated temperature[9].

With the inclusion of Sodium hydroxide and GGBS into fly ash concrete, fly ash/slag concrete showed a reduction in setting time[10]. Both GGBS and PFA reduce creep on concrete. When cement is replaced with 30% of PFA, the creep reduced to around 50%. GGBS concrete showed similar or lower creep when the replacement level of GGBS is around 30% to 70% [11, 12]. An increase in GGBS content would increase the water to binder ratio, due to its higher specific surface area. The early strength of GGBS/cement concrete was lower than cement concrete because of the slow formation of calcium hydroxide. As the curing time increase, the strength achieved in GGBS concrete was higher than that in cement concrete[13]. The addition of GGBS into cement reduces the pore size in hardened cementitious material which will prevent the intrusion of chloride ions into the concrete. The decrease of permeability to chloride and sulphate attack will prevent the corrosion of steel structure in reinforced concrete structure[14].

The hardened process of concrete can be accelerated by high temperature curing. Steam curing significantly increased the early strength of slag/cement mortar as proven by Sajedi [15]. The strength of PFA concrete is accelerated through steam curing as proven by Liu [16]. Steam curing is more preferable in precast concrete plants, as for the acceleration in strength of concrete. Steam curing at atmospheric pressure is the combination of moist curing and high temperature curing, where the continuous supply of water vapor such as that in moist curing and cured at temperature of above 100°C are available at the same time[17]. Steam curing has to apply with care. Most precast industry applied steam curing to concrete sample immediately after the concrete is casted. During the hardened process of cement, hydration heat will be released. An external heat applied to concrete before setting time will lead to thermal expansion and internal cracks and hence reduce the strength[18]. Before the concrete is

hardened, time is needed to transfer heat from the outer surface into the inner part of the concrete; the inner part of the concrete is still plastic at this stage. When an external heat is supplied to the concrete, it accelerates the hardening process at the outer surface, leaving a hardened shell surrounded by a plastic internal core. When the external heat and hydration heat reach the inner core structure, excessive heat would cause the internal expansion and result in cracks from internal to external surface [17, 19]. To prevent such problem, steam curing should be applied when the concrete is set [20].

There are a few objectives to be drawn in this study. First, the feasibility of alkaline activation of PFA/GGBS concretes without using strong alkalies such as sodium hydroxide or potassium hydroxide. Next, the feasibility of sodium carbonate/sodium silicate to replace sodium hydroxide/sodium silicate as an alkaline activator. Lastly, the strength development of alkaline activated PFA/GGBS before and after undergoing steam curing to be studied.

Experimental Procedure

Materials

Fly Ash

Fly ash is obtained from the combustion of the precipitated unit of local coal-fuel power plant. PFA has a specific surface area of 3244 cm²/g and specific gravity of 2.8. The X-ray diffraction pattern shows the presence of several oxides, the main oxides found are silica, alumina, ferrite and calcium oxide, which make up of 43.22%, 17.61%, 13.73% and 11.28% respectively. Other oxides were found in minor quantities, namely MgO, Na₂O, P₂O₅, K₂O, TiO₂ and MnO. SiO₂, Al₂O₃ and Fe₂O₃ are pozzolanic oxides which totally made up of 74.56%. Fly ash particles are mostly in spherical shape.

Ground Granulated Blast Furnace Slag (GGBS)

GGBS is the byproduct derived from steel and iron industry. GGBS is obtained during the mixing of iron-ore, coke and limestone in the blast furnace at the temperature of 1500°C. GGBS source obtained from YTL Berhad is in granulated form. GGBS in granulated form is not reactive as the specific surface area is low. Before GGBS is used, it is ground in the ball mill so that its size can pass through 8µm sieve. Specific area of GGBS after ground is found to be 4650 cm²/g by carried out Blaine finest test. Specific gravity is 2.86. From XRD results, there are abundant of Al₂O₃, SiO₂, and CaO presented in GGBS, which is 13.27%, 32.84% and 40.80% respectively.

Fine Aggregates and Mixing Water

Fine aggregates are obtained from the quartzitic natural river in an unrush manner. The specific gravity of fine aggregates is 2.65 and the maximum aggregate size is about 5mm. The sand is heated to saturated surface dried so it can be readily used for mortar mix. With reference to BS812: Part 102, fine aggregates are graded, and the overall grading limits of fine aggregates grading were referred to BS 882. The finest modulus of fine aggregates is 3.26. Local water source is obtained as the mixing water. Water used in mixing concrete is fulfilling the requirement of BS 3148: 1980. Water is treated and supplied by Perbadanan Bekalan Air (PBA).

Alkaline Activator

3.3M of sodium carbonate and 10M of sodium silicate are used as the alkaline activator. Sodium carbonate is added to 8% of total binder weight and sodium silicate is added to 10% of total binder weight. The reason of setting the molarities of sodium carbonate at 3.3M is due to the saturation of the solution at this molarities. Further increase the molarities will cause precipitation of sodium carbonate.

Mixing Procedure

The amount of sodium silicate to be included into the mix design is determined first. After getting the optimum amount of sodium silicate, the amount of sodium carbonate to be added into the mix is determined. Mortar is prepared by dry mixing all the binders and fine aggregates for 10 minutes. Water will be added and mix for 2 minutes. Flow table test will be carried out to ensure the required flow is achieved. If the required flow is not achieved, water will be added again, and mix for another 1 minute. Then the flow table test will be carried out again. These steps are repeated until the desired flow, which is between 140mm to 160mm is achieved. Controlled specimens were moist cured for 7 days and 28 days. Steam Curing specimens were moist cured for 7 days and steam cured for 5 hours. The strength is compared with 7 days strength and 28 days strength of controlled specimens. Table 1 below shows the mix design for the optimisation of sodium silicate amount. Table 2 shows the optimisation of sodium carbonate amount.

Table 1 Optimisation of Sodium Silicate

Percentage of sodium silicate	GGBS (kg/m ³)	PFA (kg/m ³)	H ₂ O (kg/m ³)	Sand (kg/m ³)	Sodium silicate (kg/m ³)
2	236.91	355.36	177.68	1628.74	11.85
4	235.24	352.86	176.43	1617.26	11.76
6	233.59	350.39	175.19	1605.95	11.68
8	231.97	347.95	173.98	1594.80	11.60
10	230.37	345.56	172.78	1583.80	11.52

Table 2 Optimisation of sodium silicate and sodium hydroxide ratio

Na ₂ CO ₃ : Na ₂ SiO ₃ ratio	GGBS (kg/m ³)	PFA (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Na ₂ CO ₃ (kg/m ³)	Na ₂ SiO ₃ (kg/m ³)
2:6	231.85	347.77	255.03	1593.94	11.59	34.78
4:6	230.13	345.19	253.14	1582.11	23.01	34.52
6:6	228.43	342.64	239.85	1570.45	34.26	34.26
8:6	226.76	340.14	255.10	1558.96	45.35	34.01
10:6	225.11	337.67	225.11	1547.64	56.28	33.77
12:6	223.49	335.23	234.66	1536.49	67.05	33.52
14:6	221.89	332.83	244.08	1525.49	77.66	33.28
2:8	230.25	345.37	247.52	1582.95	11.51	46.05
4:8	228.55	342.83	251.41	1571.28	22.86	45.71
6:8	226.88	340.32	243.89	1559.78	34.03	45.38
8:8	225.23	337.84	242.12	1548.45	45.05	45.05
10:8	223.60	335.41	229.19	1537.28	55.90	44.72
12:8	222.00	333.01	233.10	1526.27	66.60	44.40
14:8	220.42	330.64	231.45	1515.42	77.15	44.08
2:10	228.67	343.01	268.69	1572.12	11.43	57.17
4:10	227.00	340.50	249.70	1560.60	22.70	56.75
6:10	225.35	338.02	247.88	1549.26	33.80	56.34
8:10	223.72	335.58	251.69	1538.08	44.74	55.93
10:10	222.12	333.18	260.99	1527.06	55.53	55.53
12:10	220.54	330.81	253.62	1516.20	66.16	55.13
14:10	218.98	328.47	257.30	1505.49	76.64	54.74

Results And Discussion

Notes

7D flex is 7 days moist curing flexural strength

7D COM is 7 days moist curing compressive strength

7S FLEX is 7 days moist curing + 5 hours steam curing flexural strength

7S COM is 7 days moist curing + 5 hours steam curing compressive strength

28D FLEX is 28 days moist curing flexural strength

28D COM IS 28 days moist curing compressive strength

Figure 1 Flexural Strength of Sample with Different Amount of Na₂SiO₃

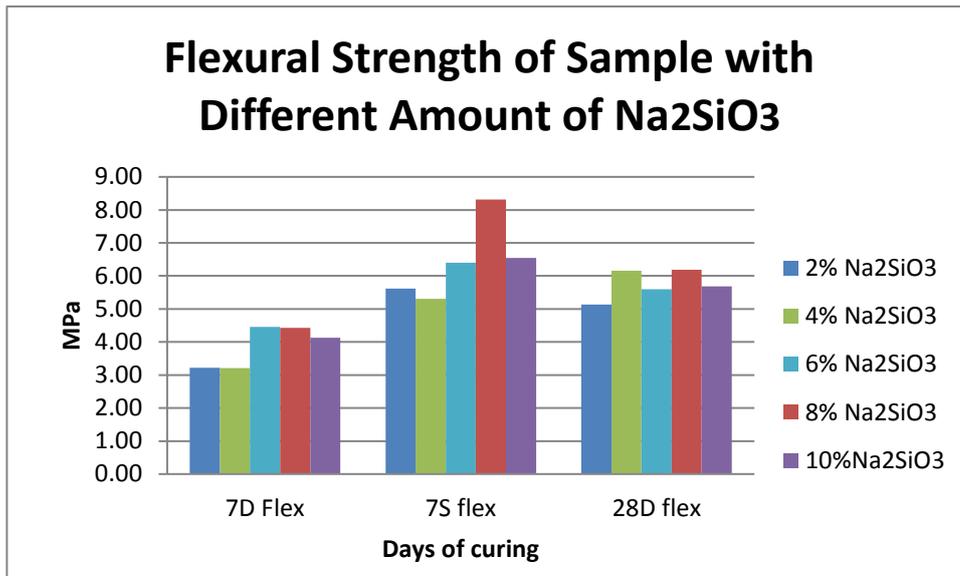


Figure 2 Compressive strength of Sample with Different Amount of Na₂SiO₃

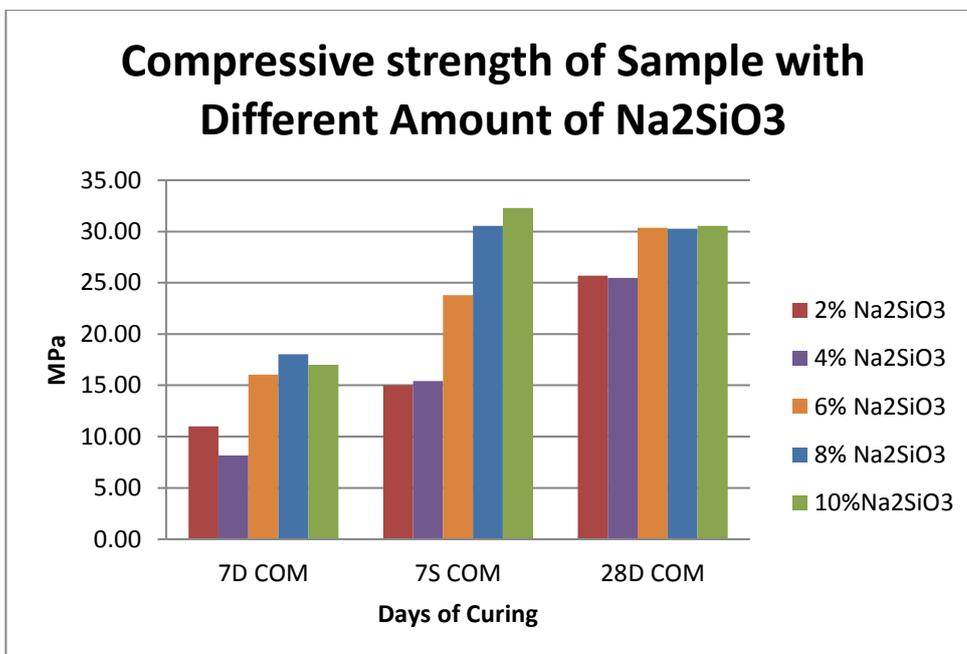
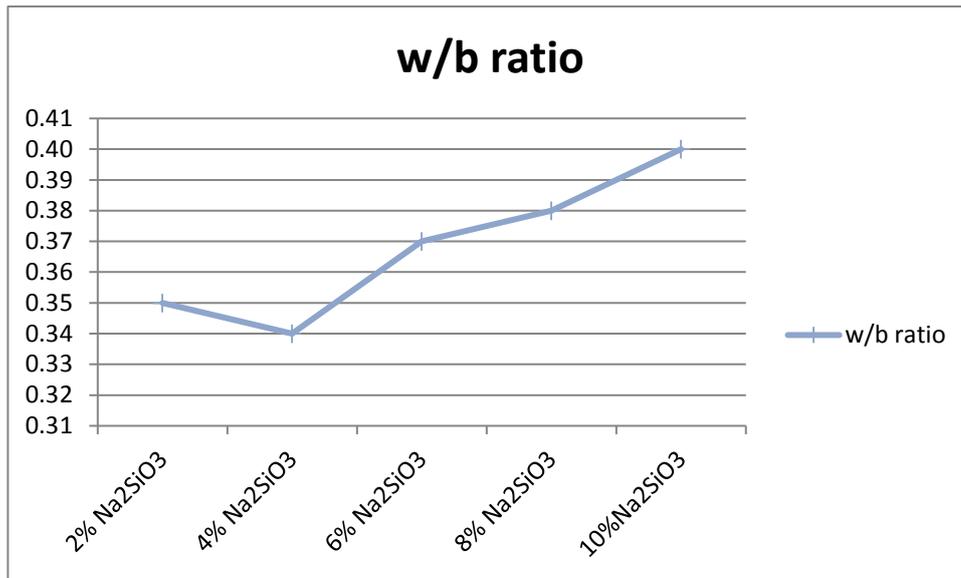


Figure 3 Water to Binder Ratio for Sample with Different Sodium Silicate Content



In Figure 1 and Figure 2, the dosage of sodium silicates and curing conditions were studied. It can be noticed that when the amount of sodium silicate increased from 4% to 6%, there was a great improvement in both flexural and compressive strength in all testing ages. The flexural strength of sample contained 4% sodium silicate at 7 days was 3.21 MPa, the compressive strength was 8.18MPa. The flexural strength of sample contained 6% sodium silicate at 7 days was 4.45MPa, the compressive strength was 16.03MPa. It can be clearly seen that the compressive strength at 7 days for the sample contained 6% sodium silicate was double to the one contained 4% sodium silicate. The flexural strength of the samples increased significantly from the increment of 4% of sodium silicate to 6% of sodium silicate. Though the flexural strength decreased slightly when a higher amount of sodium silicate is used, it did not affect the compressive strength development of the sample. All samples gained the strength rapidly between 7 days and 28 days. As the hydration of PFA is slow, the increment of sodium silicate provide enough silicate ions to react with the calcium ions from GGBS, hence, the more C-A-S-H gel can be formed and the strength can be enhanced at the early age[21]. The strength development from 7days to 28 days is contributed to the hydration of the PFA. The hydration of PFA is depended on the alkalinity of the pore solution. The hydration of PFA will start after 7 days. The water to binder ratio increases with an increase in sodium silicate amount. This is because the dissolution of silicate occur during the initial setting stage, thus more water is required for the dissolution reaction [22]. All the samples have a rapid strength development when subjected to steam curing, and the strength achieved is equivalent to 28 days strength. The hydration of fly ash and formation of C-S-H gel can be accelerated by high temperature[23].

Figure 4 Flexural Strength of Sodium Carbonate and Sodium Silicate Activated Sample at different composition

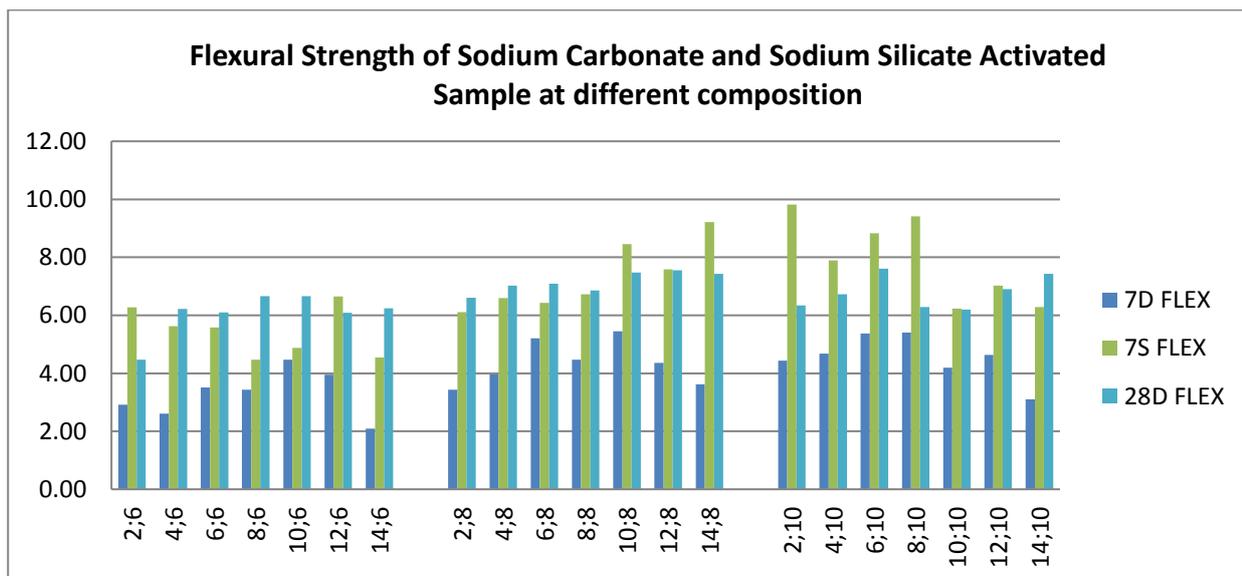
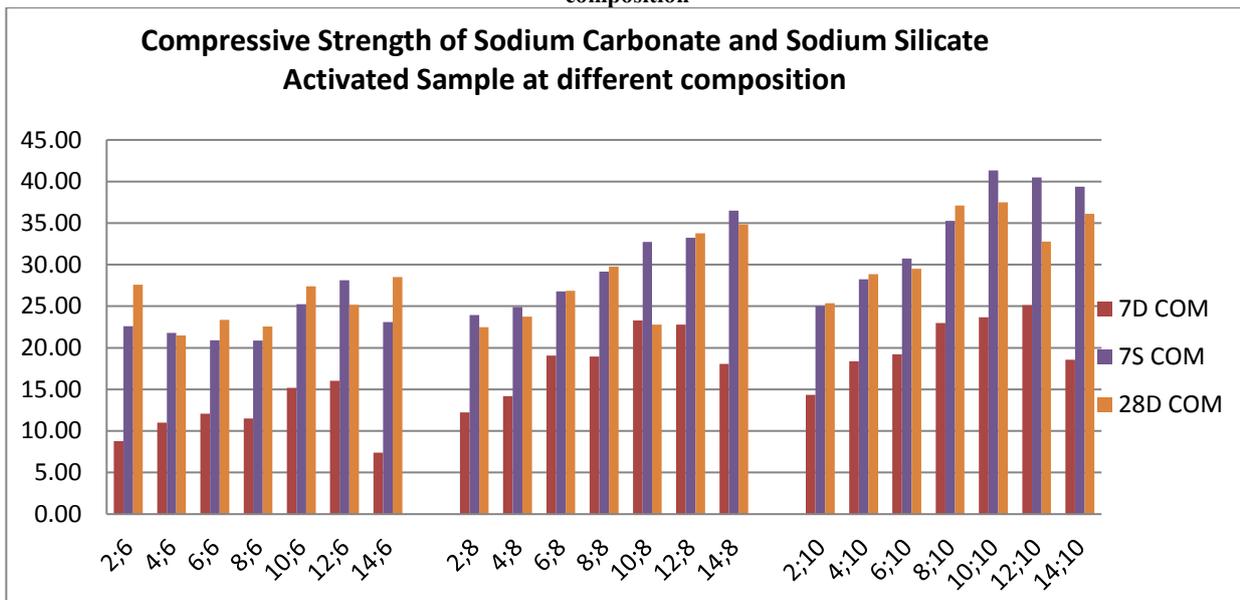


Figure 5 Compressive Strength of Sodium Carbonate and Sodium Silicate Activated Sample at different composition



The mix design was further modified by the addition of sodium carbonate as a secondary alkaline activator. The improvement in strength with inclusion of sodium carbonate was not prominent for the sample with sodium carbonate + 6% sodium carbonate. When 12% of sodium carbonate is added together with 6% of sodium silicate, the flexural strength achieved is 3.96MPa and compressive strength achieved is 16.02MPa, which is not much difference with the strength achieved without addition of sodium carbonate. The sample with 6% sodium silicate achieved a flexural strength of 4.45MPa and compressive strength is 16.03MPa.

When 6% of sodium carbonate and 8% of sodium silicate was added to the sample, flexural strength achieved was 5.21MPa and compressive strength was 19.06MPa. Highest strength was achieved when 12% of sodium carbonate was added. The 7 days flexural strength and compressive strength is 4.36MPa and 22.79MPa respectively. 33.76MPa and 7.55MPa of compressive strength and flexural strength achieved on 28 days. The steam curing strength achieved was 7.59MPa and 33.25MPa for flexural and compressive respectively.

Optimum strength is achieved when 8 % of sodium carbonate and 10% of sodium silicate was used together as the alkaline activator. The 7days compressive and flexural strength recorded to be 22.98MPa and 5.41MPa respectively. 28 days compressive strength recorded was 37.11MPa and flexural strength recorded was 6.29MPa. The steam cured sample achieved the flexural strength of 9.41MPa and 35.28MPa. The sample which only contained 8% sodium silicate as the activator, the 7 days compressive strength achieved is 17.02MPa, flexural strength is 4.13MPa. 28 days compressive strength is 30.56MPa and flexural strength is 5.68MPa. Steam curing sample achieves 6.55MPa and 32.28MPa. From the comparison, it is obvious that inclusion of sodium carbonate can improve the strength development of fly ash/slag mortar sample.

From Figure 4 and Figure 5, it can be seen that increasing amount of sodium carbonate increase the strength. Higher alkali content indicates that higher sodium oxide presented. It aided the dissolution of silicon dioxide (SiO_2) and aluminium dioxide (Al_2O_3) which is mainly from slag and partly from PFA. The extent of reaction increase and so the strength increased [24].

Conclusion

1. The alkaline activation of PFA/GGBS concrete can be carried out without using sodium hydroxide. The alkaline activation of PFA/GGBS concrete by sodium silicate alone is able to achieve sufficient strength after 28 days.
2. Sodium Carbonate and Sodium silicate are suitable as the activator for PFA/GGBS mortar. Sodium carbonate has a pH of about 9.8, which is less corrosive than sodium hydroxide and adequate to provide an alkaline environment for geopolymerisation process to be initiated. Sodium carbonate can be an alternative to sodium hydroxide since sufficient strength can be achieved both in early age and latter age.
3. Steam curing is efficient in increasing the early strength of geopolymer concrete to the strength equivalent to 28 days strength. Due to the high temperature of steam, C-S-H gel formation and hydration process is accelerated. Steam cure the PFA/Slag mortar for 5 hours is adequate to achieve a high strength. When early strength is required, steam curing is preferable, otherwise, the concrete still can achieve sufficient strength after 28 days.

Acknowledgement

The authors would like to thank Ministry of Education, Malaysia for funded this research under Fundamental Research Grant Scheme (FRGS) No. 203/PPBGN/6711347. Research funding received from Universiti Sains Malaysia under the USM RU Grant (1001/PPBGN/814211) and USM Short Term Grant (304/PPBGN/6312106) is also gratefully acknowledged.

References

- Liu, B., et al., *Influence of ultrafine fly ash composite on the fluidity and compressive strength of concrete*. Cement and Concrete Research, 2000. **30**(9): p. 1489-1493.
- Duxson, P., et al., *Geopolymer technology: the current state of the art*. Journal of Materials Science, 2007. **42**(9): p. 2917-2933.
- Diaz, E., E. Allouche, and S. Eklund, *Factors affecting the suitability of fly ash as source material for geopolymers*. Fuel, 2010. **89**(5): p. 992-996.
- Hardjito, D., et al., *On the development of fly ash-based geopolymer concrete*. ACI Materials Journal-American Concrete Institute, 2004. **101**(6): p. 467-472.
- Rangan, B.V., *Fly ash-based geopolymer concrete*. 2008.
- Atiş, C.D., *Heat evolution of high-volume fly ash concrete*. Cement and Concrete Research, 2002. **32**(5): p. 751-756.
- Consoli, N.C., C.G. da Rocha, and C. Silvani, *Devising dosages for soil-fly ash-lime blends based on tensile strength controlling equations*. Construction and Building Materials, 2014. **55**: p. 238-245.
- Zhang, J., et al., *Monitoring setting and hardening of concrete by active acoustic method: Effects of water-to-cement ratio and pozzolanic materials*. Construction and Building Materials, 2015. **88**: p. 118-125.
- Ravina, D. *Efficient concrete utilization of coarse and fine fly ash in precast concrete by incorporating thermal curing*. in *Journal Proceedings*. 1981.
- Lee, N.K. and H.K. Lee, *Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature*. Construction and Building Materials, 2013. **47**(0): p. 1201-1209.
- J. J. Brooks, P.J.W. and M. Boukendakji, *Influence of Slag Type and Replacement Level on Strength Elasticity, Shrinkage and Creep of Concrete*. Special Publication, 1992. **132**.
- Bamforth, P., *8366 In situ measurement of the effect of partial Portland cement replacement using either fly ash or ground granulated blast-furnace slag on the performance of mass concrete*. 1980.
- Oner, A. and S. Akyuz, *An experimental study on optimum usage of GGBS for the compressive strength of concrete*. Cement and Concrete Composites, 2007. **29**(6): p. 505-514.
- Cheng, A., et al., *Influence of GGBS on durability and corrosion behavior of reinforced concrete*. Materials Chemistry and Physics, 2005. **93**(2): p. 404-411.
- Sajedi, F., *Effect of curing regime and temperature on the compressive strength of cement-slag mortars*. Construction and Building Materials, 2012. **36**: p. 549-556.
- Liu, B., Y. Xie, and J. Li, *Influence of steam curing on the compressive strength of concrete containing supplementary cementing materials*. Cement and Concrete Research, 2005. **35**(5): p. 994-998.
- Hanson, J.A., *Optimum Steam Curing Procedure in Precasting Plants*. Journal Proceedings, 1963. **60**(1).
- Alexanderson, J., *Strength Losses in Heat Cured Concrete*. 1972: Svenska forskningsinstitutet cement och betong.
- Joesph, J.S. and H.C. Wilbur, *Early Strength of Concrete as Affected by Steam Curing Temperatures*. Journal Proceedings, 1949. **46**(12).
- Ramezaniapour, A.A., M.H. Khazali, and P. Vosoughi, *Effect of steam curing cycles on strength and durability of SCC: A case study in precast concrete*. Construction and Building Materials, 2013. **49**: p. 807-813.
- Brough, A.R. and A. Atkinson, *Sodium silicate-based, alkali-activated slag mortars: Part I. Strength, hydration and microstructure*. Cement and Concrete Research, 2002. **32**(6): p. 865-879.
- Bapat, J.D., *Mineral Admixtures in Cement and Concrete*. 2012: CRC Press.
- Baoju, L., et al., *Some factors affecting early compressive strength of steam-curing concrete with ultrafine fly ash*. Cement and Concrete Research, 2001. **31**(10): p. 1455-1458.
- Abdalqader, A.F., F. Jin, and A. Al-Tabbaa, *Development of greener alkali-activated cement: utilisation of sodium carbonate for activating slag and fly ash mixtures*. Journal of Cleaner Production, 2016. **113**: p. 66-75.