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Optimisation on the Hybridisation Ratio of Pulverised Fuel Ash and Ground Granulated Blast Furnace Slag (PFA - GGBS) for the Fabrication of Geopolymer Mortar

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***Abstract* — The current cement industry has several environmental and social problems, including high greenhouse gas emissions, air pollution, water consumption, and the generation of large quantities of waste. This matter has grown into a significant concern, and there is now a pressing requirement to substitute the conventional binding material in concrete, namely Ordinary Portland Cement (OPC). This paper presents the report on the hybridisation of two industrial by-products, namely pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS), to produce an alternative binder known as geopolymer. A set of 11 hybrid PFA-GGBS geopolymeric mortar mixes was created using the complete range of hybridisation ratios, along with different water-to-binder ratios. The freshly mixed hybrid PFA-GGBS geopolymeric mortar was put through a flow table test to examine the required water-to-binder ratio to achieve the targeted level of workability. Afterward, all the samples were allowed to cure at room temperature before undergoing a destructive test to measure their compressive strength. According to the study's findings, the highest compressive strength of 4.6 MPa was achieved with a PFA-GGBS hybridisation ratio of 60-40 in the geopolymeric mortar. However, when the content of GGBS exceeded 40 %, the compressive strength of the hybrid PFA-GGBS geopolymeric mortar produced tended to decrease. Additionally, as the replacement level of GGBS increased, the required water-to-binder ratio also increased to maintain the targeted level of workability, ranging between 0.31-0.41. The PFA-GGBS hybridisation ratios of 60/40, 50/50, 40/60, and 30/70 have shown promising properties to be further refined regarding their application in cementless concrete. Moreover, the study conducted to replace cement as a binder in concrete has the potential to make the construction industry more sustainable and reduce carbon emissions by utilising industrial waste ash that would need to be affordable, strong, durable, and widely available in order to be practical.**

Keywords* — *Hybrid, Geopolymer, Compressive Strength, PFA, GGBS

I. INTRODUCTION

In order to support expanding urbanisation and meet the needs of the growing population, there is a rising need for cement worldwide in the building industry. The traditional binder matrix for concrete, ordinary Portland Cement (OPC), has a very significant detrimental impact on the environment. The cement industry is responsible for approximately 8% of global carbon dioxide emissions, according to the International Energy Agency (IEA) [1]. Other greenhouse gases, such as methane and nitrous oxide, are also emitted by the industry, but carbon dioxide is the most significant contributor to its greenhouse gas emissions. One of the methods to minimise the carbon footprint effect and to promote the sustainability of the construction industry, an alternative binder, namely geopolymer can be studied. Geopolymer is a type of inorganic polymer that is formed from the reaction of

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aluminosilicate materials with alkaline activators, such as sodium or potassium hydroxide. Additionally, geopolymers can be made from a wide range of source materials, including industrial waste materials such as fly ash and slag, which can help reduce waste and provide a sustainable use for these materials. Geopolymers can have similar properties to traditional materials like cement but with lower greenhouse gas emissions and improved durability. They are used in various applications, such as construction materials, refractory materials, and environmental remediation [2-4].

On the other hand, a relatively limited study has been done to evaluate the performance of hybrid industrial waste ash comprising pulverised fuel ash (PFA) and ground granulated blast furnace slag. In light of this, the research focuses on the compressive strength, workability, and water/binder ratio of a hybrid PFA-GGBS geopolymer mortar. In addition to that, the purpose of this research is to develop a new category of binder that can be manufactured for producing cementless concrete.

II. MATERIALS AND METHODS

A. Materials

The materials utilised in this experiment for the development of hybrid PFA-GGBS mortar include PFA, GGBS, and washed river sand. PFA is a by-product of coal combustion for electricity generation in Malaysia. PFA was acquired from the precipitator unit of a nearby coal-fired power station for this investigation. PFA was discovered to have a specific gravity of 2.80, a specific surface area of 3240 cm^2/g, and a loss on ignition (LOI) of 1.80 %, respectively. The PFA used in this work is classified as class F with CaO content of less than 10 %.

GGBS originates as a by-product of the iron-making process. It is obtained by quenching molten iron slag from a blast furnace with water or steam, which causes it to cool rapidly and solidify into a glassy, granular material. The GGBS utilised in this experiment was obtained from YTL Berhad. It was established that GGBS had a specific gravity of 2.86 and a specific surface area of 4650 cm^2/g. Table I displays the elemental composition of the PFA and GGBS utilised.

Locally procured, undisturbed quartzitic natural river sand with a specific gravity of 2.65 and a maximum aggregate size of 5 mm was utilised as fine aggregate. In order to be used as a component material in hybrid PFA-GGBS mortar mixtures, the fine aggregate was prepared to a saturated surface-dry state. The grading of the fine aggregates followed the overall grading limitations of BS 882 and followed BS812: Part 102. It was discovered that the fine aggregates' fineness modulus was 3.26. As for mixing water, potable water from the local water supply system was utilised.

Table I: Elemental composition of PFA and GGBS.

Elemental Composition	% by total mass	
	PFA	GGBS
MgO	5.94	6.08
Al_2O_3	17.61	13.27
SiO_2	43.22	32.84
P_2O_5	0.23	0.01
SO_3	-	-
K_2O	1.31	0.36
CaO	10.28	40.8
TiO_2	0.88	0.47
MnO	0.14	0.14
Fe_2O_3	13.73	0.28
C	1.80	-
Loss on ignition (%)	1.80	5.55

B. Methods

For all hybrid PFA-GGBS mortar mixtures, the ratio of binder to sand was maintained at 1:2.25. The hybridisation ratio starts with 100% PFA as the control mix and then gradually replaced by GGBS at increments of 10 % by total binder weight. These translate to PFA-GGBS hybridisation ratios of 100/0, 90/10, 80/20, 70/30, 60/40, 50/60, 40/60, 30/70, 20/80, 10/90, and 0/100, respectively, on a weight basis. Meanwhile, each hybrid PFA-GGBS mortar mixture's water-to-binder ratio was adjusted until it reached the appropriate consistency of 50 ± 5 % mortar flow. Table II summarises the hybrid PFA-GGBS mortar mixtures proportion and the flow of the mortar mixture.

An epicyclic mixer was used to homogenise each batch of hybrid PFA-GGBS mortar. Freshly mixed mortar mixtures were subjected to an ASTM Flow test utilising the flow table specified in ASTM C230, while ASTM C109 was used to determine the compressive strength of mortar. An edge dimension of 50 mm mortar cube specimen was moulded and vibratory compacted. The sample is then subjected to moist curing at room temperature until it achieves the testing ages of 7 and 28 days.

Table II: Mix proportion and mortar flow of hybrid PFA-GGBS. geopolymer.

Mix designation	PFA (kg/m^3)	GGBS (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	w/b ratio	Mortar flow (%)
P100G0	665	0	1496	206	0.31	50
P90G10	595	66	1487	212	0.32	50
P80G20	526	131	1478	217	0.33	50
P70G30	457	196	1469	222	0.34	50
P60G40	389	260	1460	227	0.35	55
P50G50	323	323	1452	232	0.36	55
P40G60	257	385	1443	237	0.37	55
P30G70	191	446	1435	242	0.38	55
P20G80	127	507	1426	247	0.39	50
P10G90	63	567	1418	252	0.40	50
P0G100	0	627	1410	257	0.41	50

III. RESULTS AND DISCUSSION

A. Compressive Strength of Hybrid PFA-GGBS Geopolymer Mortar

Figure 1 displays the ultimate compressive strength of hybrid PFA-GGBS geopolymer mortar mixtures at 7 and 28 days of testing ages. Compared to the control mix P100G0, the introduction of GGBS in addition to PFA had a substantial effect on each mixture's compressive strength for geopolymer mortar. From 10 % to 40 % replacement level of GGBS, the compressive strength of the hybrid PFA-GGBS mortar mixes begins to rise; then from 50 % to 100 % replacement level of GGBS, the compressive strength starts to reduce. This pattern occurs for both ages. Additionally, it was shown that more significant compressive strengths could be attained when GGBS content was dominant in hybrid PFA-GGBS mixtures P50G50, P40G60, and P30G70. This is primarily because of GGBS's high calcium content encourages early strength development [5].

A significant compressive strength gain rate was observed to occur at the early age of specimen on 7 days of curing duration but at a lower rate compared to 28 days compressive strength gains. The highest development of the geopolymeric composites compressive strength occurs on the 28 days of curing. This is likely caused by the high content of unreactive silica and alumina in PFA, which can limit the formation of the geopolymer network and slow down the strength development. Additionally, the presence of impurities in PFA, such as carbon and organic matter, can also affect the reaction kinetics and lead to slower strength development [6]. By that, the optimum hybrid PFA-GGBS geopolymer mixture, namely P70G30, P60G40, P50G50, and P40G60, must be further refined by including an alkaline activator to increase the extent of geopolymerization and improvement in strength development.

Looking more closely at this pattern reveals that the most favourable PFA-GGBS hybridisation ratio should be 60/40 at both ages, producing the highest compressive strengths of 2.0 MPa and 4.6 MPa after 7 and 28 days, respectively. A number of additional hybrid PFA-GGBS geopolymer mixes, including P70G30, P60G40, P50G50, and P40G60, had significant improvement potential in terms of its compressive strength. The aforementioned hybrid PFA-GGBS mixtures could be further studied to produce cementless concrete.

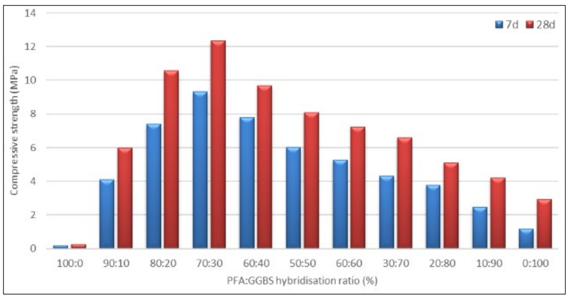

Fig. 1. Compressive strength of PFA-GGBS geopolymer mortar.

B. Water: Binder Ratio of Hybrid PFA-GGBS Geopolymer Mortar

The water/binder ratio of freshly mixed hybrid PFA-GGBS mortar mixture needed to reach the desired consistency is shown in Fig. 2. The results show that the water/binder ratio rises when GGBS substitution is increased. To maintain the necessary level of mixture consistency, the water/binder ratio should increase by 0.01 for every 10 % increase in GGBS content relative to the weight of the whole binder. The difference in specific surface area between GGBS, which is 4650 cm^2/g and the specific surface area of PFA is 3240 cm^2/g, is the reason for this. The total specific area of the hybrid PFA-GGBS geopolymer mixtures that must be wet will expand with the replacement of PFA with GGBS in the mixtures. By that, the increased the water:binder ratio is significantly affected by the inclusion of GGBS into the hybrid PFA-GGBS geopolymer mixtures [7].

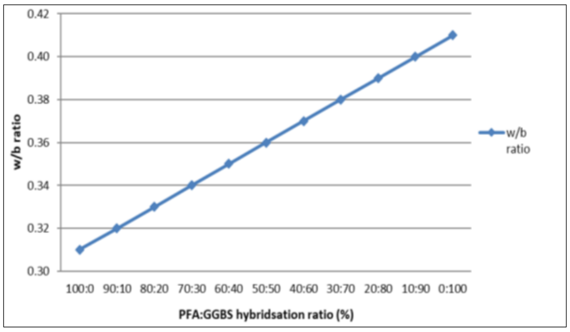

Fig. 2. Compressive strength of PFA-GGBS geopolymer mortar.

IV. CONCLUSION

The results of this research demonstrate the compressive strength and water demand of hybrid PFA-GGBS geopolymer mortar at varied hybridisation ratios. Compared to the control mortar (P100G0), geopolymeric mortar incorporated with GGBS by total binder weight displayed greater compressive strength. In this investigation, 40% substitution of PFA with GGBS is the best amount to produce the maximum compressive strength for the hybrid PFA-GGBS mortar mixture. Furthermore, the addition of GGBS raises the water demand of the hybrid PFA-GGBS mortar mixture to maintain the workability at a consistent level. P70G30, P60G40, P50G50, and P40G60 are some of the hybrid PFA-GGBS mortar mixtures that might potentially be studied further by adding an alkaline activator to improve their mechanical and durability qualities so that it can be used as an alternative binder to replace cement in the construction industry.

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