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Binary Effect of Fly Ash and Waste Glass on Compressive Strength and Heat of Hydration for Concrete

Lee Yet Hui[1], Zalipah Jamellodin[2*], Mohammad Soffi Md Noh[3], Suraya Hani Adnan[4], Rendy Thamrin[5]

[1]Primareka Sdn Bhd, No. 9A, Jalan Kenari 2, Bandar Puchong Jaya, 47100 Puchong, Selangor, MALAYSIA

[2]Advanced Concrete Material Focus Group, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[3]Big Data Focus Group, Jamilus Research Centre, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[4]Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Muar, MALAYSIA

[5]Department of Civil Engineering, Faculty of Engineering, Andalas University, Padang 25163, INDONESIA

*Corresponding Author

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Abstract: The most crucial building material in the modern construction industry is concrete. Concrete made of components like cement and aggregates. Cement was a significant contributor to the carbon dioxide emissions that altered the world's climate and had other detrimental effects on the environment. Concrete is used so frequently in the construction industry that it is crucial to conduct research on this topic since it will affect how long a structure lasts. In an effort to decrease the detrimental effects on the environment and enhance the qualities of concrete, alternative materials, such as fly ash (FA) and waste glass (WG), have been utilised to replace some of the fine aggregate and ordinary Portland cement (OPC), respectively. Compressive strength testing and hydration heat assessment were used in this study. Fly ash and waste glass were substituted for normal concrete in amounts ranging from 5 to 25% by weight of the cement and fine aggregate, respectively. For the compressive strength test, 36 concrete cubes with dimensions of 100 mm x 100 mm x 100 mm were created. They were evaluated after 7 and 28 days. Six (6) new concrete samples of 150 mm in diameter and 300 mm in height were prepared in order to access the heat of hydration of concrete. According to the study, the concrete with 5% replacement of FA and WG had the highest compressive strength at both 7 and 28 days, according to the results, out of all the tested mixes. In addition, 13 hours after casting, the control concrete mix design recorded the 37°C peak temperature, which was the highest of all the concrete mixes.

Keywords: Compressive strength, heat of hydration, fly ash, waste glass

*Corresponding author: zalipah@uthm.edu.my

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1. Introduction

Concrete is one of the main construction materials wisely used for building structures worldwide. It is the substance that are second most consumed in the world after water (Gagg, 2014). Predictions state that by the year 2050, the amount of concrete produced could increase by up to 18 million metric tonnes (Monteiro, 2006). Concrete can be used in many applications such as foundation, superstructures, floor construction, exterior surface, dams, roads and bridge. It is highly difficult to imagine a construction world without concrete as construction material. The properties such as durability, strength and versatility are the reasons that make concrete irreplaceable in construction. However, concrete's properties can be affected by the change of contents in concrete. Concrete is made from several materials which consisting mainly of cement, water and aggregates. The type of aggregate or cement used can affect the quality of concrete in term of strength. Aggregates in concrete are generally designated as either fine or coarse. Fine aggregates are ranging from 0.025 to 6.5 mm while coarse aggregates are from 6.5 to 38 mm or larger. The aggregate must be clean and free from other admixture as it can cause chemical reaction which can affect the properties of the concrete. Furthermore, cement is the cementing agent that binds aggregates together to form concrete. The partial replacement of ordinary Portland Cement (OPC) and fine aggregate (FG) with fly ah (FA) and waste glass (WG) respectively in the production of concrete will influence the concrete's properties such as strength.

Fly ash like volcanic ash and is the product of coal burning power plant. It is residue that left from burning coal. Normally, it is finer than the OPC and the major chemical constituents are silica, alumina and oxides of iron and calcium. Most of the FA has characteristic of pozzolanic and sometimes self-cementitious. Therefore, it is often used as a mineral admixture in concrete (Joshi and Lohita, 1997). The potential replacement of cement by FA in concrete has been mentioned since the very beginning of the nineteenth century (Chakraborty and Banerjee, 2016). However, the use of FA in concrete only starting to grow in the last 50 years. Typically, FA is replaced to cement range from 15% to 25% by weight of the cement. The actual amount used of the FA in partial cement substitution is depending on the application, location of the structure, specification limits, and climate (Kiran and Ratnam, 2014).

Only 10% of the 600 tonnes of new bottles that are produced each day by Malaysia's three glass bottle makers are returned to the factory to be utilised to create more bottles. Around 900 thousand tonnes of glass debris were generated in 2004, of which 300 thousand tonnes were recycled in Poland (Tamana et. al 2013). This also indicated that glass still ends up in landfills in large quantities. Utilizing of WG as partial substitute materials for FG is one of the positive way for sustainable development. As one of the earliest man-made materials, it comes in a range of shapes and sizes, including container glass, bulb glass and cathode ray tube glass. All of these glasses have a short lifespan in their original form and must be reused or recycled in order to avoid environmental issues that would arise if they were disposed in landfills. Furthermore, glass might be pozzolanic when the size of the particles less than 75 μm as it is a material that contains high silica content (Ali, 2015). This increases the possibility of the replacement of WG with aggregates in concrete to avoid serious pollution problems.

Every year, concrete is claimed to be responsible for 4-8% of the carbon dioxide (CO_2) in the world (Leon and Phil, 2016). The emission of CO_2 causes significant negative impact and contribute to global warming. However, the impact of concrete production on environment can be minimized by replacing the cement and aggregate with waste materials such as FA and WG. Furthermore, it is important that concrete possess high compressive strength as it often used as a compressive member in the application of column and foundation. If one unexpected high load suddenly applied to the concrete structure that with insufficient compressive strength, that load might exceed the load bearing capacity of the structure resulting catastrophic failure. Replacing OPC with alternative material such as FA allow the concrete to obtain in long-term strength (Yoo et al, (2017).

The heat of hydration is known as the quantity of heat lost, evolved upon complete hydration at a given temperature (Jamellodin et. al (2018), Meh et. al (2022). The methods for determining its value are stated in BS4550: Part 3: Section 3.8: 1978 and ASTM C186-05. The rate of heat development is important as compared to the total heat of hydration for the investigation on early age concrete because the total heat over long time will be dissipated. Therefore, it will be resulting the rise of temperature become lesser. In the case of Portland cement, it is normally 50% of the total heat will be liberated in the first 3 days. Around 75% and 90% of the total heat are estimated to be liberated in first week and half year respectively. Furthermore, the chemical composition of cement is also the factor that influencing the heat of hydration of cement. The heat of hydration when their corresponding quantities by mass hydrated individually is nearly equivalent to the total heat of hydration of its individual pure components.

2. Materials and Test Methods

This research is aim to use FA and WG partially replace OPC and FG at percentage 5, 10, 15, 20 and 25% by the weight of OPC and FG. Various samples of concrete cube and cylinder that containing different percentages of mixtures of WG and FA were prepared. The tests that conducted was compression test and heat of hydration test.

2.1 Selection and Preparation of Fly Ash and Waste Glass

Ordinary Portland cement was obtained from the UTHM laboratory. Class F FA was used obtained from Tanjung Bin power plant, Pontian, Johor. The WG that used in this study was obtained and collected from the Sustainable Campus Office (SCO) recycling center, UTHM. The collected WG was grinded by using a grinder. After that, it was sieved through a sieve plate with 5 mm of opening, only the WG with size less than or equal to 5 mm was used for the fine aggregate replacement. Moreover, the grinded WG was subjected to the sieve analysis in order to compare its grading level with the grading level of fine aggregate as well as standard grading limit that stated in the standard BS EN 12620:2002. Fig. 1 shows grinded WG with the maximum size of 5 mm.

Fig. 1 - Grinded WG with the maximum size of 5 mm

2.2 Concrete Materials and Mixes

The mix design proportion of the control sample was determined by using the normal concrete mix design method.

Table 1 shows a normal concrete mix design for 1 m^3 of the control sample. Six different types of concrete mixes were produced and each type of concrete mix was represented by different partial replacement percentages of OPC and FG by weight as illustrated in Table 2. While the water content, coarse aggregate content was constant for all mixes.

Table 1 - Normal concrete mix design for 1 m^3

Materials	Quantity (kg)
Ordinary Portland cement	310
Coarse aggregate (10 mm)	450
Coarse aggregate (20 mm)	900
Fine aggregate	635
Water	170

Table 2 - Mix design concrete proportion (% content)

Mix No.	Symbol	Ordinary Portland Cement (OPC)	Fly Ash (FA)	Fine Aggregate (FG)	Waste Glass (WG)
Mix 1	100-OPC-FG	100	0	100	0
Mix 2	5-FA-WG	95	5	95	5
Mix 3	10-FA-WG	90	10	90	10
Mix 4	15-FA-WG	85	15	85	15
Mix 5	20-FA-WG	80	20	80	20
Mix 6	25-FA-WG	75	25	75	20

2.3 Determination of Compressive Strength

Compressive strength test was carried out by using cube size 100mm x 100mm x 100mm according to BS EN12390-3:2002. Compression test was done after 7 and 28 days curing for all six-mix design. Three cube specimens were used for each mix proportion to test the compressive strength of concrete. All presented measured strengths of concrete are the average values of the corresponding three specimens.

2.4 Measurement of Heat of Hydration

Plywood with dimensions of 300 mm x 300 mm x 450 mm was prepared as the outside mould in this experiment. It was enclosed with 76 mm of thick polystyrene that served as insulation. Fresh concrete was immediately poured into a PVC cylinder pipe with a 150 mm diameter and 300 mm height, as shown in Fig. 2. The data logger system was then connected to a thermocouple (Type K), as shown in Fig. 3, that had been put into the centre of each box. For each concrete composition, temperature measurements were taken over a period of five days. The test setup and an insulated cubical box are shown in Figs. 4 and 5.

The heat generated by the hydration process was released when the concrete was poured into a cylindrical mould, raising the temperature of the concrete mass. Changes in hydration temperature are observed more frequently in the first 24 hours and at smaller intervals thereafter, until the temperature is close to the initial value. The mix design proportion hydration temperature measurements were done for almost 5 days.

Fig. 2 - Pouring concrete into mould

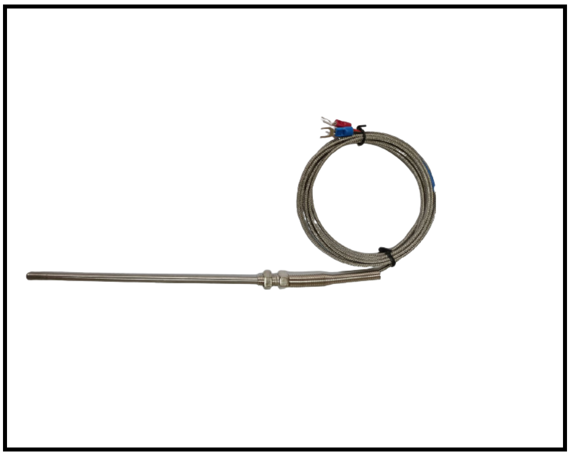

Fig. 3 - Thermocouple Type K

Fig. 4 - Hydration temperature of concrete testing equipment

Fig. 5 - System for recording temperature data via a data logger

3. Results and Discussion

3.1 Compressive Strength of Concrete

For the various percentages of OPC and FG replacement by FA and WG, respectively, the compressive strength of 5% FA and WG replacement in Mix 2 recorded the highest compressive strength for 7 and 28 days. Control specimen, Mix 1 achieved the second-highest compressive strength after 7 days of curing, at 27.8MPa. The remaining mix proportions have a lower compressive strength compared to the control, Mix 1. Mix 6 had the lowest compressive strength 18.8 MPa for 7 days curing.

All concrete mixes reached the 30MPa design strength after 28 days. The Mix 2 with 5% substitution of FA and WG had the maximum compressive strength, measuring 36.8 MPa, 12.2% higher than the control mix. Additionally, Mix 3 and Mix 4 concrete showed compressive values of 34.5 MPa and 34.3 MPa, respectively, when compared to the control specimen Mix 1. There were around 5.18% and 4.57% increases compared to the control specimen. When the replacement was higher than 15%, the compressive strength was lower than the control mix.

Mixes 5 and 6 had compressive strengths of 31.3 MPa and 30.5 MPa, respectively, which were 4.57% and 7.01% less than the control mix. The previous study by Rao et al. showed a similar finding that the compressive strength started to decline and recorded lower compressive strength than the control mix when the waste glass powder exceeded 15% (Rao et. al, 2020).

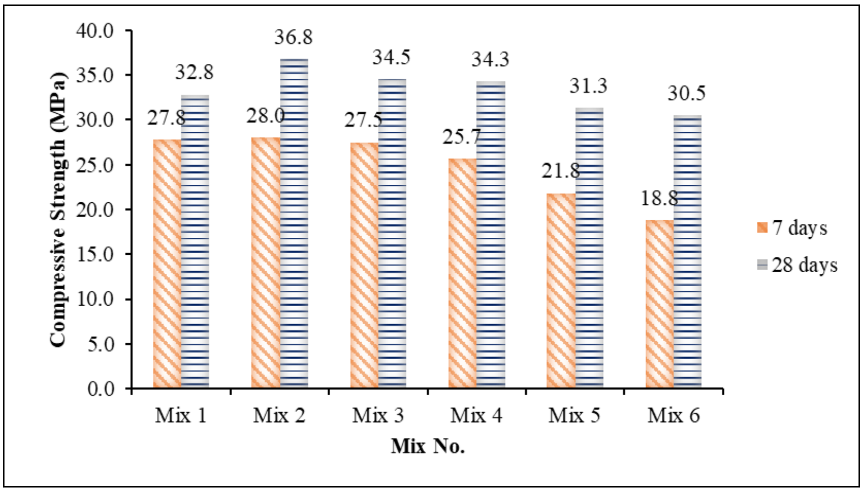

Fig. 6 - Compressive strength of concrete at 7 and 28 days with various FA and WG replacement percentages

3.2 Heat of Hydration of Concrete

Table 3 and Fig. 7 show how the heat of hydration developed from various mix proportions. It has been noted that the beginning temperature and time taken for all concrete mixtures with various FA and WG replacement percentages to achieve their peak temperatures are comparable. All mixes took between 12 and 14 hours to reach their maximum temperature after mixing. The control specimen, Mix 1, recorded the highest temperature of 37 °C at 13 hours after casting. The lowest peak temperature and longest duration for achieving peak temperature was 34.6 °C for the concrete produced with 25% substitution of FA and WG, Mix 6. Additionally, the peak temperature of concrete with 5% FA and WG peaks at 35.7 °C after 13 hours casting, while concrete with 15% FA and WG replacement peaks at 35.5 °C after 12 hours. The peak temperatures for Mix 3 and Mix 5 were 34.7 °C at 14 hours and 34.9 °C at 13 hours, respectively. After the peak temperature was recorded, it was seen that the heat of hydration output gradually decreased until the temperature of all mixes remained constant. The final temperature reported for all specimens was in the range of 26 °C – 27.5 °C.

Table 3 - Characteristics of Concrete's Heat of Hydration

Mix No.	Symbol	Initial temperature (°C)	Peak temperature (°C)	Time since mixing to peak temperature (hours)
Mix 1	100-OPC-FG	25.5	37.0	13
Mix 2	5-FA-WG	25.5	35.7	13
Mix 3	10-FA-WG	25.5	34.7	14
Mix 4	15-FA-WG	25.5	35.5	12
Mix 5	20-FA-WG	25.5	34.9	13
Mix 6	25-FA-WG	25.5	34.6	14

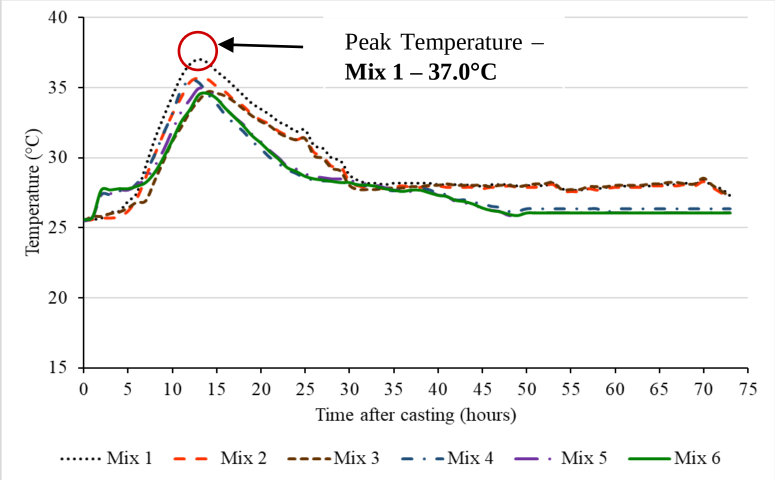

Fig. 7 - The development of hydration temperature

4. Conclusion

According to the results, the compressive strength of normal concrete has been marginally enhanced by replacing OPC with FA and FG with WG. However, when replacing reached 20% or more, the compressive strength of concrete was decreased. For Mix 2, the ideal ratio for replacing FA and WG is. The concrete's greatest strengths at 7 and 28 days were 28 MPa and 36.8 MPa when 5% of FA and 5% of WG were partially substituted for OPC and FG. Additionally, it was noted that the strength of the concrete for that mix was roughly 93% of the typical strength of concrete after 7 days. In addition, all concrete mixtures attained 30 MPa or more after 28 days, despite the fact that concrete with 25% replacement of FA and WG failed to meet the preset characteristic strength (70% of characteristic strength) at 7 days. It demonstrates how a pozzolanic material like FA can partially replace OPC to create a long term strength.

The data for the measurement of heat of hydration showed that the time it takes for the temperature to reach its maximum in concrete with various FA and WG percentages was comparable. Even though the percentage of concrete varied, it was somewhere between 12 and 14 hours. In addition, when compared to other mixes that had varying mix proportions, the peak temperature for control mix, Mix 1 was recorded the highest value. Although the end temperature was higher than that of other mixes, the control mix design had the greatest temperature. All of the concrete mixtures' ultimate temperatures fell between 26 to 27.5 °C. A concrete mixture using 25% FA and WG produced the lowest peak temperature.

It was found that substituting FA and WG did not reduce the heat of hydration produced by the curing and hardening paste. The quantity of $Ca(OH)_2$ created during cement hydration and the reactivity of the materials utilised determine the hydration temperature of concrete. FA has extremely low CaO, hence the amount of $Ca(OH)_2$ in the hydration products should be decreased.

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