Influence of High Volume Fly Ash in Controlling Heat of Hydration of Concrete

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ABSTRACT

This paper highlights test results on the influence of high volume fly ash in controlling the heat of hydration in concrete. Four concrete mixes namely, concrete containing 100% ordinary Portland cement as control, and high volume fly ash concrete i.e. concrete containing 40, 50 and 60% fly ash were prepared. The temperature rise due to heat of hydration in all the mixes was recorded. It has been found that fly ash significantly reduced the total temperature rise in concrete. The result obtained and the observation made demonstrate that the high volume replacement of cement by fly ash is advantageous, particularly for mass concrete where thermal cracking due to excessive heat rise is of great concern.

Keywords: **Portland cement, pozzolan, high volume fly ash, hydration, temperature rise.**

1.INTRODUCTION

The silicate and aluminates of cement react in the presence water to form a binding medium, which solidifies into hardened mass. During this process an exothermic reaction takes place where heat is generated within the concrete matrix and is liberated to the surroundings. In other words, when cement is hydrated the compound reacts with water to acquire stable low-energy states, and the process is accompanied by the release of energy in the form of heat [1, 2]. The quantity of heat evolved upon complete hydration of a certain amount of unhydrated cement at a given temperature is defined as heat of hydration [2]. The heat generated by the cement's hydration raises the temperature of concrete, which is the result of exothermic chemical reaction between cement and water. The total amount of heat liberated and the rate of heat liberation from hydration of individual compounds can be used as indices of their reactivity [3]. Heat of hydration in concrete is generally influence by materials used; a vigilant choice of material can therefore minimize or maximize the heat liberation in concrete.

Over the years the rise of temperature in concrete with various mix proportions has been studied. If the temperature rise is significantly high and the concrete undergoes non-uniform or rapid cooling, stress due to thermal contraction in conjunction with structural restraint can result in cracking before or after the concrete eventually cools to the surrounding temperature [4]. The major constituents of Portland cement is calcium, in the form of tri-calcium silicate, tri-calcium aluminate and di-calcium aluminate, in which compound of tri-calcium silicate and aluminates generate more heat at faster rate than di-calcium silicate and other cement compounds. Development of heat in concrete therefore depends on the total cement content in the mix. High cement quantity in concrete may be beneficial to obtain higher early strength, but greater heat developments occur due to chemical reactions which produces undesirable cracks and shrinkages in concrete [5,6]. High fineness of cement provides a greater surface area to be wetted, resulting in an accelerating the reaction between cement and water. This causes an increase in the rate of heat liberation at initial ages, but may not influence the total amount of heat developed over several weeks [4]. Other factors that influence heat development in concrete are water-cement ratio, placing and curing temperature, the presence of chemical and mineral admixture and the dimension of the structural element. It is obvious that admixtures that accelerate hydration also accelerate heat liberation and those that retard hydration delay heat development.

Use of pozzolanic materials such as fly ash, rice hush ash, silica fume and palm oil fuel ash has been found to influence the concrete by lowering the adiabatic heat in concrete. Unlike OPC, pozzolan start reacting somewhat slowly with the calcium hydroxide produced by the clinker hydration and therefore, at least initially it behaves like an inert diluting agent towards the Portland cement which it has been mixed. These phenomena results in a reduced rate of heat evolution i.e. rise in temperature and reduce ultimate heat of hydration [1, 3, 7].

High volume fly ash concrete has emerged as construction material to overcome the draw backs associated with the production and use of Portland cement. The high volume fly ash application in concrete also reduces the severe environmental hazards caused by the disposal problem. This type of concrete usually contains more than 50% of mineral admixture by weight of binder. The concept minimizes the amount of OPC required to produce high-quality concrete in different types of applications [8]. The application of high volume fly ash has also been reported to have lowered the autogenous temperature raise of concrete by 25°C [9]. This study therefore presents some experimental results on the effect of high volume fly ash in reducing heat of hydration of concrete.

2. MATERIALS AND TEST METHOD

2.1 Collection and preparation of fly ash

Fly ash is an inorganic, non-combustible waste product of coal-burning power plants. As coal is burnt at high temperatures, carbon is burnt off and great amount of the mineral impurities are carried away by the flue gas in the form of ash. The molten ash cooled rapidly and solidifies as spherical, glassy particle.

Fly ash is abundantly available in Malaysia, since the use of pulverised coal firing remains one of the ways of generating electricity in country. The fly ash used in this study was obtained from Tanjung Bin Power Plant which is located at Pontian of Johor, southern state of Malaysia. The fly ash particles were collected using electrostatic precipitator and stored in silo. The fly ash is obtained in powder form and no further grinding is carried out on the ash.

2.2 Cement

The cement used in this study was ordinary Portland cement (OPC) obtained from a single source. The physical properties and chemical composition of the OPC are also shown in the Table 1.

2.3 Aggregate

A saturated surface dry local river sand with fineness modulus of 2.9, passing through sieve size of 4.75mm having specific gravity and water absorption of 2.6 and of 0.70% respectively was used as fine aggregate. While the coarse aggregate was 10mm crushed granite with specific gravity of 2.7 and water absorption of 0.5% was used throughout the research work.

2.4 Water

The quality of water plays an important role in controlling properties of concrete. In this study, municipal water supplied to the concrete laboratory was used for concrete mixing.

2.5 Concrete mixes

In the present study two concrete mixes were made: one with OPC alone and the others with OPC replaced by weight of 40, 50 and 60% fly ash. These replacement levels were considered in view of the strength development obtained in the mix, the details of the mix proportions of the concrete are shown in Table 1.

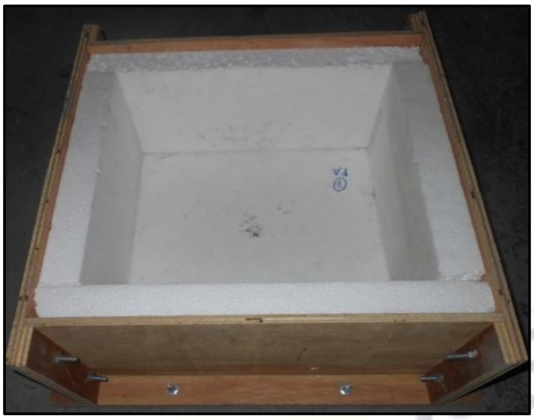
Table 1: Mix proportion and heat of hydration characteristics of OPC and fly ash concrete

Materials/properties	OPC concrete	40% Fly ash concrete	50% Fly ash concrete	60% Fly ash concrete
OPC (kg/m^3)	420	252	210	168
Fly ash (kg/m^3)	0	168	210	252
Fine aggregate (kg/m^3)	815	815	815	815
Coarse aggregate (kg/m^3)	994	994	994	994
Water (kg/m^3)	185	185	185	185
Superplasticizer (l/m^3)	2.94	2.94	2.94	2.94

2.6 Measurement of heat of hydration

Concrete is characterized with generation and liberation of heat to surroundings during chemical reaction. The temperature rise due to heat of hydration eventually turns into concern of durability, particularly in mass concrete. The rise in temperature due to heat of hydration of cement, when no heat is lost or gain from the surrounding environment is termed as adiabatic temperature rise of concrete [1,7]. One of the means of attaining this condition is by perfect insulation of concrete, even though this is rarely achieved in practical cases.

The method of measurement of heat of hydration suggested by Awal and Hussin [3] and Awal and Shehu, 2013[7] was used in this investigation. A cubical plywood of sides 500mm internally pact with 76mm thick expanded polystyrene acting as the insulator. Each concrete mix (one with 100% OPC and the other with OPC replaced by weight of 40, 50 and 60% fly ash) was cast into the cubical plywood with internal dimensions of 300mm. Prior to casting, thermocouple was inserted into the centre of each box through the drilled hole of the polypropylene foam lid and was connected to a SR1 temperature/humidity digital controller instrument to obtain temperature readings from each box. Arrangement of the cubical box and test instrument is shown in Fig 1.



An insulated plywood box

Test setup

Fig. 1: Internal view of an insulated plywood box and test arrangement.

When concrete was poured into the box, heat was liberated by hydration process that subsequently increased the temperature of the concrete mass. This increase in temperature and subsequent drop was monitored with close interval during the first 24 hours and lesser frequency afterwards until the temperature dropped close to the initial reading. The measurement continued up 120 hours for all the mixes.

3. RESULTS AND DISCUSSION

3.1 Physical and chemical properties of fly ash

Fly ash is precipitated from the exhaust of a coal burning power station. The burning of coal leaves two residues behind that formed into fly ash and bottom ash. Majority of fly ash particles are glassy in appearance and spherical in shape; a typical electron micrograph of fly ash is shown in Fig.2. However, fly ash is much finer than OPC and it has a specific gravity of 2.23 and Blaine fineness of 3600 cm^2/g. The ash has a wide range of particle sizes, with 21.5% particle retained on 45µm sieve.

The chemical composition, illustrated in Table 1, reveals that fly ash is moderately rich in silica content (49.88%) as compared to that of OPC (18.11%). The CaO content, however, is very low i.e. about 5.92%. The sum of silica, alumina and iron oxide is 80.30%, which satisfies the requirement to be classified as class N according to the standard specified in ASTM C618 [10].

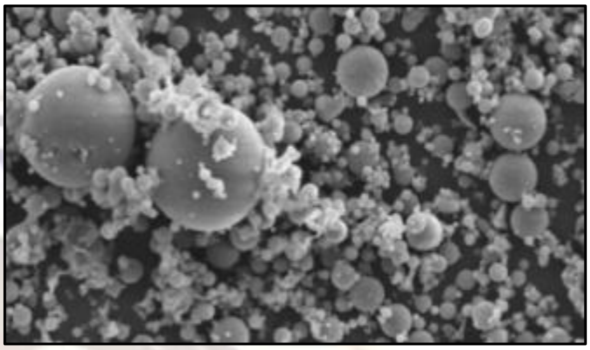


Fig. 2: Scanning electron micrograph of fly ash.

Table 2: Physical and chemical properties of OPC and fly ash

Test	OPC	Fly ash
Physical properties		
Fineness-Blaine surface area(cm^2/g)	3400	3600
Specific gravity	3.12	2.23
Residue on 45µm sieve (%)	- -	21.5
Chemical composition (%)		
Silicon dioxide (SiO_2)	18.11	49.88
Aluminium oxide (Al_2O_3)	3.07	25.32
Ferric oxide (Fe_2O_3)	3.03	5.31
Calcium oxide (CaO)	65.88	5.92
Magnesium oxide (MgO)	1.87	1.51
Sulphur trioxide (SO_3)	3.37	0.62
Sodium oxide (Na_2O)	0.47	0.83
Potassium oxide (K_2O)	0.19	0.89
Loss on ignition (LOI)	1.38	2.86
28-day Strength activity index with OPC (%)	--	86

Other compounds such as magnesium oxide, sulphur trioxide and potassium oxide are in fair distribution. The amount of carbon present in any ash varies depending on the combustion process. Loss on ignition, for example detected in this study is 2.86% and is within the maximum of 10% stipulated in ASTM C 618 [10]. The 28-day strength activity index of fly ash with OPC has been found to be significantly higher (86%) than the minimum value (75%) prescribed in the same standard. Although, the activity index is not a direct measure to be considered as a magnitude of compressive strength, but is an indication of reactivity with a given cement to evaluate the contribution of the ash to the strength development of concrete.

3.2 Workability and compressive strength

Workability of OPC and high volume fly ash concrete was measured in terms of slump. A moderate slump value of 65, 85, 90 and 110mm were observed for OPC, 40, 50 and 60% fly ash concrete respectively as shown in Table 3. It can be seen that higher replacement of cement with fly ash resulted in increasing the workability of the fly ash concrete compared to that of OPC alone. Regarding strength, a higher compressive strength value was obtained in OPC concrete, while samples containing 40, 50 and 60 % replacement made up 85, 72 and 63% respectively of the control sample strength at 28 days. Similar trend have been reported [11-13] of concrete containing high volume fly ash.

Table 3: Workability and compressive strength

Type of concrete	Slump (mm)	28-day compressive strength (MPa)
OPC	65	44.0
40% Fly ash	85	37.4
50% Fly ash	90	31.7
60% Fly ash	110	27.6

3.3 Heat of hydration of concrete

Fig. 3 reveals the record of heat liberation obtained at mid depth of concrete during hydration process in all the concrete mixes. The time-temperature histories along with the concrete mix proportions, however, are shown in Table 4. It can be observed that during the initial period, the temperature rise for all the mixes was almost equal. But has the duration increases effect of high volume replacement of OPC with fly ash can definitely be detected. Firstly, concrete containing high volume fly ash at 40, 50 and 60% was found to reduce the peak of heat of hydration by 16.4, 23.5 and 28.5% respectively when compare with the OPC concrete. Both the OPC and high volume fly ash concretes eventually showed a gradual drop in temperature until a relatively steady state was attained during the period of study.

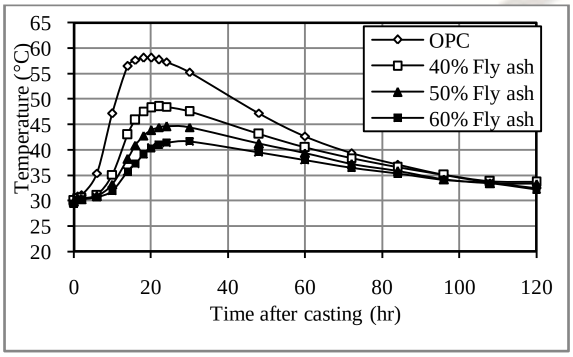


Fig. 3: Development of temperature in OPC and fly ash concrete.

Table 4: Temperature and time history of OPC and fly ash concrete

Materials/ properties	OPC concrete	40% Fly ash concrete	50% Fly ash concrete	60% Fly ash concrete
Initial temperature (°C)	30.15	30.03	29.90	30.23
Peak temperature (°C)	58.13	48.56	44.68	41.73
Time since mixing to peak temperature (hr)	19	22	26	29

It is generally known that fineness of cement influences the rate of heat development to some extent. In spite of the higher surface area of fly ash, no adverse effect had been detected during the period of study. Neither the peak temperature obtained for fly ash concrete was recorded to be higher nor was the time to reach the highest peak early as compared to OPC concrete. In both ways fly ash concrete performed better than the control.

Though not with fly ash, a similar trend has been reported by Awal and Shehu [7], who observed a lower temperature rise in concrete containing high volume palm oil fuel ash. While no further tests were conducted to evaluate the fineness of the fly ash on heat of hydration, the lower cement content in the mixes and the pozzolanic behaviour of the ash would, indeed, be responsible for the reduction of heat of hydration in fly ash concrete. A close observation, though with slag concrete noted by Swamy [14] concluded that the slag fineness not only ensured high strength but also high early strength without enhancing the heat of hydration.

4. CONCLUSIONS

From the laboratory results and the discussion made, it can be concluded that fly ash is a pozzolanic material and has been characterised to be a good supplementary cementing material in concrete. Using fly ash as cement replacement in concrete has resulted in a reduction on the maximum temperature rise under adiabatic curing condition. The results obtained and the observations made in this study clearly demonstrate that high volume fly ash has good potentials in controlling heat of hydration of concrete. Although a reduction in strength gain has been observed, the higher volume replacement of cement by fly ash is advantageous, particularly for mass concrete where thermal cracking due to excessive heat rise is of great concern.

5. ACKNOWLEDGEMENT

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