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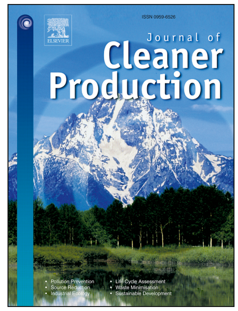

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Abstract

This paper presents an experimental study on the workability and the heat of hydration in Self-compacting concrete (SCC) incorporating agro-industrial waste and blended aggregates. The control mixture contained only Ordinary Portland Cement (OPC) as the binder while the remaining mixtures incorporated binary and ternary cementitious blends of OPC, palm oil fuel ash (POFA) and fly ash. The replacement of waste was from 10% to 40% by mass of the total cementitious material of the concrete for workability test and limited to 30% and 40% replacement for the heat of evaluation test. Workability i.e. passing ability, filling ability and segregation resistance was determined and semi-adiabatic temperature rise during the initial stage of hydration was measured by thermocouples. It was observed that fly ash mixes required the least amount of super-plasticiser (SP) to obtain a workable SCC, however, POFA mixes had the reverse effect. The ternary use of POFA and fly ash had better workability properties than the POFA mixes and performed the best in terms of segregation resistance. The ternary mixes also had the lowest amount of heat dissipation with peak temperatures occurring earlier than the fly ash mixes. The experimental studies indicate that ternary blend SCC with POFA and fly ash has significant potential when considering a sustainable

construction material hence also providing a cleaner production solution for the palm oil industry.

Keywords: Self-compacting; concrete; workability; palm oil fuel ash; fly ash; heat of hydration; binary blend; ternary blend

1. Introduction

Concrete is one of the most important elements for any kind of construction work and composed of mainly cement, aggregate, water and chemical admixtures. Generally, concrete is compacted by a vibrator or steel bar after being placed inside the formwork to remove the entrapped air after which it becomes a dense and homogeneous material. Compaction is very important in order to produce a uniform concrete mix with desired strength and durability properties.

Self-compacting concrete (SCC) is an innovative construction material that has been developed in concrete technology. It is competent to flow, filling all areas and corners of the formwork even in the presence of congested reinforcement and compacts under its own weight. SCC requires three fresh concrete properties including filling ability, passing ability and adequate segregation resistance (EFNARC, 2002; PCI, 2003; EGSCC, 2005; and TESTING-SCC, 2005)

The main hypothesis for SCC is the reduction of course aggregate and the increase of the cement content to maintain its fresh state properties and homogeneity. High cement content increases overall concrete production cost, generates high heat during the hydration process, and increases creep and shrinkage problems. Thus significant quantities of pozzolanic material including fly ash, rice husk ash, silica fume, granulated glass blast-furnace slag and bagasse ash are used to replace cement in order to improve the fresh state properties, control generation of heat and to reduce creep and shrinkage problems (Sua-Iam and Makul, 2013; Sua-Iam and Makul, 2014; Rahman et.al., 2014; Thomas and Gupta, 2013). It is also indirectly beneficial for the environment due to the reduction of carbon dioxide emissions associated with the manufacture of Portland cement clinker (Yang et al., 2014).

Fly ash is an industrial waste that is produced in furnaces of coal burning power plants. It comprises, predominantly, of very fine spherical glassy particles collected in the dust collection systems from the exhaust gases of fossil fuel power plants (Jones and McCarthy, 2006). The dominant minerals in fly ash are quartz, kaolinite, illite, and siderite (Sua-Iam and Makul, 2015) whereas the main chemical constituents are silica, alumina and oxides of iron and calcium, which can react with calcium hydroxide to form calcium silicate hydrate and calcium aluminate hydrate.

The utilization of fly ash in concrete as partial replacement of cement is gaining popularity. This is mainly due to the improvements on the fresh state and hardened state of concrete combined with ecological and cost benefits. Malhotra (1998) reported that the water demand gets reduced by up to 20% for normal vibrated concrete and that Class C fly ash required less SP than Class F fly ash to achieve the same workability. In practice, the quantity of fly ash to replace cement is limited to 15 to 20% by mass of the total cementitious material (Bendaputi, 2011). Many studies suggest that the maximum use of 30% fly ash results in excellent workability (Kim et al., 1996; Miura et al. 1993; Ponikiewski and Gołaszewski, 2014) and others demonstrates that high volume fly ash of up 70% replacement in SCC, can significantly enhance fresh properties of concrete (Bouzabaa and Lachemi, 2003; Dinakar et al., 2008). Khatib (2006) in his research of SCC incorporating fly ash of up to 80% concluded that concrete containing fly ash will cause an increase in workability at constant water to binder (w/b) ratio and SP content. W/b ratio refers to the total cement content including the pozzolanic supplementary cementitious material to the water ratio. Liu (2010) suggested that a lower dosage of SP and increased w/b content is required to maintain the same filling ability. In other words, incorporation of fly ash reduces the need of SP necessary to obtain a similar slump flow compared with the SCC containing only cement as binder. Similar observation was also made by Yahia et al. (1999).

Another waste material that is increasingly being researched for sustainable concrete production in South East Asia is POFA (Sata et. al., 2004). Palm oil is a popular vegetable oil for cooking and food processing (Oosterveer, 2014) and POFA is the final product when palm fruit residues are burnt for generation of electricity after the oil extraction process. Fig. 1 represents the palm oil processing and production process of POFA. As Malaysia is one of the biggest Palm Oil producers in the world (Yusoff, 2006), POFA is available in abundance.

In 2012, the Malaysian Palm Oil Board (MPOB) estimated that the total oil palm plantation area in Malaysia covers 5.07 million hectares. Over 400 palm oil mills are operating and producing large amounts of solid waste (Fig. 2) in the form of fibers, kernels and empty fruit bunches annually (MPOB, 2014). The total solid waste generated by the industry in Malaysia amounts to about ten million tonnes a year (Safiuddin et al., 2011). This agricultural waste material is disposed in landfills without any profitable return. It also creates environmental pollution and health hazards (Sumadi and Hussin et al., 1995). It is also worth noting, that from site visits to local palm oil mills, and it became apparent that there are various forms of POFA. Palm fruit goes through combustion in the furnace, rises, and is captured by particle filtration equipment before it reaches the chimney in the form of fly fuel-ash (Fig. 3). There are also particles that do not rise and are left in the bottom due to incomplete burning (Fig. 4). Incomplete burning can cause a higher carbon footprint as well as reducing the marketability of waste as supplementary cementitious materials (Yeboah, 2014). Empty fruit bunches go through burning in a separate furnace and produce a rough fibrous ash that is currently used as fertilizer and mulch.

POFA like fly ash is a pozzolanic material that has a high amount of silica content. Research shows that the silica content in POFA ranges from about 50 to 70 % of its composition (Galau and Ismail, 2010). The pozzolanicity of any material is closely related to the ability of silica to react with calcium hydroxide to produce calcium silicate hydrate (ASTM 618). The fresh concrete properties of POFA based SCC have been investigated (Safiuddin, 2010) where the dosage of POFA was limited to 15 % by mass of the total cementitious material. It was found that the filling ability and passing ability decreased and sieve segregation resistance grew with increasing POFA content. Salam et al., (2013) observed that POFA contributes to a denser microstructure, which increases the compressive strength up to 20% and reduces the permeable porosity of high strength SCC. POFA is also reported to significantly reduce the total temperature rise in concrete (Awal and Shehu, 2013).

There has been a growing interest in the use of fly ash with another pozzolanic material as ternary blends with OPC to improve the properties of concrete. In evaluating mix proportions of fly ash and silica fume, Sahmaran (2006) demonstrated that the slump flow of the ternary blends provided better performance than the binary blends. Gesoglu et. al. (2012) observed that using marble powder or limestone filler by itself in SCC mixtures resulted in increased amount of SP to achieve the target slump flow diameter. However, with the inclusion of fly ash in the ternary mixtures, the amount of SP required remarkably decreased due to the viscosity modifying property of fly ash. Recently, Hassan et al., (2014) investigated the use of blended POFA and pulverized burnt clay to produce self-compacting mortars. They concluded that pulverized burnt clay could be used to improve the fresh properties of mortars. Various other researchers (Makhloufi et al., 2012; Rizwan and Bier, 2012; Sua-iam and Makul, 2013) also made similar observation with the use of ternary blended mineral admixtures such as rice husk ash, blast furnace slag, or natural pozzolans with OPC. Utilization of waste in any composite material will enhance the sustainability, solve a number of environmental waste problems (Al-Oqla and Sapuan, 2014) and could create a cleaner production for the palm oil industry.

Heat evolves from the hydration of cement. From previous reports it is apparent that the influence of different pozzolans on the rate of heat evolution and the amount of heat evolved in hydrating binary or ternary blends is highly complex (Snelson et al., 2008). The heat of hydration depends on a number of factors such as the w/b, cement fineness, the ambient temperature, the chemical admixtures used, the chemical composition of the cement and the presence of any cement replacement materials etc. (Pane and Hanse, 2005; Mounanga et al., 2011; Zakoutsky et al., 2012; Kumar et.al., 2012; Nagaratnam et., 2012; Tydlitat et. al., 2014; Pathak and Siddique, 2012). Much research done, in some way or another, has constant w/b or evaluates varying w/b in concrete. However, in SCC with various cement replacement material; this becomes more complex as each mix requires different amounts of water or SP content in order to fulfill the workability requirements. Fly ash by itself improves workability (Sonebi, 2004; Khatib, 2008) and reduces the heat of hydration (Joshi and Lohtia, 1997; Atis, 2002; Amnadnua et al., 2013) in normal concrete, but POFA has the opposite effect on workability. In this study, an effort was made to evaluate the difference between the three mixes i.e POFA, fly ash and the mixture of POFA and fly ash for producing SCC. The w/b and SP content was varied in all mixes in order to maintain similar workability properties. The resulting workability and heat evolution were evaluated.

2. Experimental Program

2.1 Materials

2.1.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) grade 42.5 based on ASTM: C150 / C150M - 12 was used in concrete as cementitious material. The particle density of the cement was 2,950 kg/m3 with a specific gravity of 3.14. The Blaine specific surface area was 3,510 cm^2/g. The chemical composition is given in Table I.

2.1.2 POFA

POFA was obtained from a palm oil mill at Lambir, Miri, Sarawak, Malaysia. The POFA used in this research was the by-product of palm fruit combustion used to generate electricity. Samples were grinded in a ball mill for 8 hours. The chemical composition of POFA is given in Table I. It is worth noting that the samples were collected from the chimney and not from the bottom of the furnace. This was to ensure that the particles were dry and smaller in size with smaller carbon content. POFA from the bottom of a furnace usually consists of a greater amount of unburned materials and would require further burning and grinding.

2.1.3 Fly Ash

Low calcium fly ash, Class F as per ASTM C618, was obtained from a coal-fired power station in Sejingkat, Kuching. The coal used in this power station was mainly supplied by the coal mine in Merit Pila, Kapit, Sarawak, Malaysia. The chemical composition of the fly ash, as determined by X-Ray Fluorescence (XRF) analysis is given in Table I.

2.1.4 Course Aggregates

Coarse aggregates were composed of crushed quartzite particles, 95% of them having the size within the range of 5 mm to 10 mm. The sample was a single sized aggregate. The aggregate gradation and characteristics is shown in Table II and III.

2.1.5 Fine Aggregates

The fine aggregates consisted of locally available aggregates with a maximum size of 5 mm. Physical properties of the fine aggregates are given in Table III. Two categories of fine aggregate were chosen after various bulk density tests. Fine aggregate Type 1 was of crushed quartzite that had a size range of 600 µm to 5.0 mm as per Table IV. Fine aggregate Type 2 had a nominal size of 600 µm (uncrushed river sand) and a small amount of micro-fines (particle size of less than 75 µm) was present (see Table V for aggregate gradation). The fineness modulus for fine aggregates in this region was around 1.3 whereas in most other places it would be 2.5 and above. This demonstrates the relevance of using the coarser crushed quartzite in the mix. The fineness modulus increased to 2.7 after mixing the two types of fine aggregates.

2.1.6 Super-plasticiser

The super-plasticizer (SP) used in this research was Glenium Ace 389, supplied by BASF (Malaysia) Sdn Bhd. This SP is categorized as type F in accordance to ASTM C494 and BS EN 934-2 European Standard. It is a high range admixture that reduces the amount of water required by 12% or greater.

2.2 Mix Proportions

The mix proportions are reported in Table VI. The binder content was kept constant at 540 kg/m^3 and the replacement of total cementitious material with POFA and fly ash was from 10% to 40% by mass for workability test and limited to 30% and 40% replacement for heat of evaluation test. The ternary blends of agro-industrial waste had POFA and fly ash are in equal portions. Coarse aggregate, fine aggregate Type 1 and fine aggregate Type 2 were all kept constant at 400, 550 and 600 kg/m^3 respectively. W/b ratio varied from 0.38 to 0.44 and the SP content was kept from 0.66 to 1.4% to maintain similar workability properties of the SCC.

2.3 Mixing Method

The mixer used was a forced action cylindrical pan mixer with a vertical axis of rotation. Each batch amounted to about 0.05 m^3 of SCC mix. For an optimal mixing outcome, a specific procedure was chosen out of a number of different methods of mixing. The procedure most suited to the experiments involved putting all the aggregates into the pan and running the mixer for around 10 min. Subsequently, cement, POFA and fly ash was added and the mixer was run for approximately another 8 min until all materials were well blended. Next, the required amount of water was added slowly to the pan (poured towards, but not too close to the outer wall of the pan) and left to mix for 10 min. The SP was added at the end and run for 2 minutes.

2.4 Testing of Samples

2.4.1 Fresh state properties

Immediately after the mixing, the fresh concrete was tested for filling ability, passing ability, and segregation resistance. Standard procedures (PCI, 2003; EFNARC, 2002; EGSCC, 2005) were used to test these requirements. Slump flow and V-funnel tests were used to measure the filling ability. Slump flow measures the maximum uninterrupted flow width of SCC through a slump cone. The maximum spread and time to reach a 500mm diameter circle (T_{500}) was noted. The V-funnel flow tests were carried out according to the procedures given by European guidelines. A V-funnel flow time in the interval of 8 to 12 seconds is the time required for a mass of concrete to complete flow though the trap door of the funnel.

Passing ability was tested using J-ring test. J-ring measures the blockage of concrete due to the presence of reinforcement bars and was carried out by first holding a mass of concrete in a ‘slump cone’, placing the J-ring and then lifting the cone, thus allowing concrete to pass through the reinforcement. The maximum spread and the average concrete height difference between the centre and outside of the ring (step height) were measured.

Segregation resistance was measured through a sieve segregation test. A mass of SCC was allowed to pass through a sieve with an aperture of 4.75mm for 2 minutes. Weight of the sieved portion was then expressed as a percentage of the total weight of SCC used in the test.

2*.4.2 Evaluation of Heat*

For the purpose of studying the heat of hydration, seven cuboids (500mm inner dimension) were prepared as outer boxes and seven smaller cuboids of 300mm a side were constructed as inner moulds as per Fig. 5. All the edges were later waterproofed using a bounding agent. Each small box was insulated with 50mm of polystyrene and 25mm of glass wool on each surface. Polystyrene and the glass wool have a thermal conductivity value of 0.03W/m.K and 0.04 W/m.K respectively. All the constituents except for water and SP were promised earlier and placed in a gunny bag. This was to ensure that all the mixes were batched at about the same time for uniformity in ambient temperature and humidity. The temperature and humidity on the time of batching were 32°C and 60%.

The first cuboid was filled with concrete containing 100% OPC while the other six were cast with 30% and 40% replacement of POFA, fly ash and ternary mix of OPC, POFA and fly ash. Immediately after placing, a thermocouple (Type K) was placed through the centre of each box’s cover and into the concrete mix. This thermocouple recorded the temperature of the concrete via a data logger. The initial rise and following drop of temperature was recorded every half an hour for the first 24 hrs and subsequently every 1 – 2 hrs until the temperature stabilizes.

3. Results and Discussions

3.1 Workability

Workability tests results of SCC and performance criteria for are given in Tables VI and VII subsequently.

3.1.1 Filling Ability

Fig. 6 shows the comparison of slump flow for fly ash, POFA and the ternary blend of POFA with fly ash in OPC. All mixes were within the range of 550 – 850 mm specified by the European guidelines for SCC (EGSCC, 2005) as the slump and flow-time required for concrete to be self-compacted. Mixes that had a slump flow within the range of 660~750 falls under class SF2 of European Guidelines and is suitable for many normal applications e.g walls and columns construction. Slump flow value that was higher than 750 mm falls under the SF3 category. This is suitable for vertical applications in very congested structures, structures with complex shapes, and gives a better surface finish than SF 2.

Fig. 7 and 8 shows the T_{500} and V-funnel flow time for all mixes. A lower T_{500} and V-Funnel (VF1/VS1) flow time indicates a low plastic viscosity and implies a faster filling rate. The V-Funnel and flow time (T_{500}) was in the range of 5.52 – 12.48s and 1.49–3.71s respectively. V-funnel and T_{500} time decreases with increase in fly ash content and vice versa with POFA content.

In short, inclusion of fly ash improved filling ability where else, POFA has a reverse effect. As observed by other researchers (Bouzabaa and Lachemi, 2001; Nagaratnam et al., 2011), SP could be decreased marginally for fly ash mixes while maintaining w/b ratio at constant values. Fig. 6 also shows that fly ash mixes has a steady increment in slump flow and reached its peak diameter at 40% replacement. This could be due to the lubricating action also known as the ball bearings effect that reduces the inter-particle friction induced by the spherical nature of its particles. However, this was not the case for POFA mixes. The filling ability of POFA mixes reduced drastically at higher replacement levels. For the same amount of w/b ratio and SP content, there is lesser 'free' water. Thus it was necessary to increase the w/b ratio and the SP content in order for the mixes to be self-compactable. This could be due to its capability to absorb water or hygroscopic nature, leading to lesser 'free' water content in the mix. It was also noted, that POFA mixes were much lighter in terms of its volume compared to other mixes, had a slightly oily texture and hardened much quicker than any other samples.

The incorporation of POFA with fly ash in OPC as a ternary blend SCC gave a favorable filling ability even at 40% replacement. As seen in Fig. 6, the slump flow increased up to 820 mm for 20% replacement and dropped to 745mm at 40% replacement. The higher replacement of ternary blend exhibits lower slump. This could be largely due to the mix proportion by weight approach taken in this research. POFA, fly ash and cement has a specific gravity of 2.2, 2.7 and 3.1 respectively. Hence when volume of each material is taken into consideration, POFA contributes to a larger volume than fly ash in ternary blends and especially at higher replacement levels, POFA's hygroscopic porous structure, larger particle size, and higher specific surface area increases water demand and lowers the slump flow diameter. Sua-Iam and Makul (2013) made similar observation with ternary blend of mixes incorporating fly ash and rice husk ash.

Sahmaran et al. (2006) reports a similar slump flow for SCC incorporating fly ash and limestone powder at w/b of 0.35. In their research, the SP content was much higher at 6.75% to achieve similar workability. This variation could be due to the size and type of aggregates used in this research i.e blended aggregates with 10 mm maximum size. Also aggregates with low fineness modulus and more rounded particles improve the flow because of lower internal friction (Alexander and Prosk, 2003).

Fig. 9 shows the relationship between the T500 and V-funnel flow times. The T500 and V-Funnel flow time were within the VS2/VF2 specified by EGSCC (2005) and implies a good filling rate. The slump flow and flow times were primarily dependent on the replacement level of fly ash or POFA. To achieve a slump flow of about 750 mm for 30 and 40% replacement, the w/b ratio for ternary and fly ash blend could be maintained at 0.38, in contrast, for POFA mixes the w/b ratio had to be increased to 0.44. Similar observation was made by Safiuddin et al. (2011). They showed that fly ash has spherical and non-porous particles while agricultural waste like rice husk ash has angular and porous particles. He further reports that the physical characteristic of fly ash is responsible for greater flow spread in comparison with rice husk ash.

To conclude, an increased amount of fly ash results in improved filling ability while SP content could be reduced at constant w/b. This behavior may be attributed to the spherical shape of fly ash particles which improved the flow characteristics of SCC (Gesoglu et. al., 2012). In contrast, increasing amounts of POFA absorbed more water and produced a readily-crumbled SCC at higher replacement level and increasing the w/b ratio was necessary. The increased volume fraction and surface area of POFA requires also requires higher SP dosage at higher percentage of replacement to obtain the optimum flow spread. The dosage of SP is reduced by the inclusion of fly ash in ternary blends.

3.1.2 Passing Ability

J-ring test was carried out to investigate the passing ability of normal strength SCC. This test measured the difference in height between the concrete inside the bars and that found outside the bars. According to EGSCC, a step height of less than 15 mm forms the acceptable criteria for SCC. As seen in Fig. 10, the step height is from 5 to 15 mm and the maximum spread measured during the J-ring varies in the range of 550–760mm. The higher values indicate greater viscosity to avoid blockage of coarse aggregate when the fresh SCC flow through reinforcements.

It is evident that the incorporation of POFA into SCC has an adverse effect on passing ability. This is due to its irregular surface and hygroscopic properties. W/b ratio had to be increased in order for the samples to satisfy the passing ability criteria. However, this changes when POFA is mixed with fly ash as ternary mix performed much better than even the fly ash mixes. This is similar to Sua-Iam and Makul's (2013) observation of ternary blends that produced a SCC mix without any blocking. Gesoglu et. al. (2012) found that mixes incorporating ternary blend of fly ash performed better in passing ability than binary blends of limestone filler or marble powder. These materials by itself did not fulfill the EGSCC limitation for passing ability, however, incorporating fly ash, increased the passing ability of all the mixes.

3.1.3 Segregation Resistance

The segregation ratio is taken as the percentage of the concrete mix that has passed through a 5 mm sieve. The standard limiting value for segregation ratio is less than 20% for SR1 and 15% for SR2. As seen in Fig. 11, the segregation ratio for all mixes can be considered as consistent. This is because during the trial mix of SCC, each percentage replacement of waste materials, the w/b ratio and SP content were carefully proportioned in order to create mixes with consistent fresh-state properties. Besides that, all the mixes in this research achieved a segregation ratio of less than 15%, which may be classified as class SR2 and is even suitable to be used for tall vertical applications. From observation, it should be noted that the POFA only mixtures did not stay workable and after approximately 15 minutes started getting thicker in consistency. However, the ternary blend showed good resistance to segregation. The lower percentage of segregation indicates a higher resistance to segregation. This high segregation resistance results from a high binder content and smaller aggregate size in the mix.

It should be noted from these experiments on the fresh state properties that SCC from agro-industrial waste satisfies all the criteria of the fresh state properties of SCC, including filling ability, passing ability and segregation resistance. Higher replacement of POFA, unlike fly ash, decreases workability of SCC and showed poor consistence retention even with a higher w/b ratio. However, with the addition of fly ash, it performed better and produced a more reliable mix. Consequently, introducing POFA as a supplementary cementitious material in SCC is more productive and reliable when it is added with fly ash in terms of workability. It is also observed, that at higher fly ash replacement levels segregation resistance when the particles and lower water retention.

3.2 Evaluation of Heat

Fig. 12 represents the development of heat of hydration versus the time after casting for all mixes. Table VIII shows the initial temperature, peak temperature and the time for peak temperature. The initial rise and following drop of temperature, upon which the temperature stabilized, were collected for up to 200 hours after casting time. The temperatures were observed via a data logger and recorded manually.

All the 7 mixes underwent a series of exothermic chemical reactions. The heat evolution was dormant in the first 3.5 to 4 hrs after placing. A rapid heat evolution occurred after this relatively dormant period until it reached peak. The initial development of heat due to early hydration of the cementitious materials proved to be fairly equal, however, the peak temperatures varied significantly. The heat of hydration was highly dependent on the chemical constituents that were present in the mix. The increase in the percentage of replacement had significant effect on the heat of hydration. The highest peak temperature experienced was in the control mix at 74.3°C which occurred 14 hours after casting, whereas the samples blended with ternary binder emitted a significantly lower amount of heat at peak values. The maximum heat expelled from the mix containing 30% fly ash was 65.2°C and occurred at 20.5 hours after the mixing time, the peak was lowered by 9.1°C in comparison to OPC. All the three types of materials had a measurable effect on reducing heat. As seen in Table VIII and Fig. 13, the peak temperature of the binary mix containing 30% fly ash was noticeably higher than the one replaced by POFA. The peak temperature of 30% fly ash mix was recorded at 64.1°C, while the mix of 30% POFA reached 63.1°C, the peaks occurred 18.5 and 17.5 hours after casting respectively.

The peak temperature obtained from replacing 40% of the cement contents also confirmed the effectiveness of POFA in reducing the heat of hydration (Fig. 14). Among the mixes containing 40% of replaced material; the lowest peak temperature recorded was 57.9°C (19 hours after casting) for the mix containing POFA. On the other hand, the sample incorporating 40% fly ash achieved its peak temperature of 59.2°C at 21 hours. Ternary mixes also dissipated lesser heat than the control mix or fly ash mixes. The peak temperatures were achieved earlier than fly ash mixes. Where the cement had been replaced by pozzolanic materials, both the peak temperature and the time from casting in which the peak occurred, were greatly affected. Replacement of 40% of the cement with POFA (57.9°C) resulted in a reduction of 22% in the peak temperature compared to OPC (74.9°C).

3.3 Cost Analysis

Table IX indicates the approximate prices of various material used in the local construction industry and includes the mix design for SCC in this research, compared to conventional SCC used in Europe and Japan. The price used in this comparison is from a published data by Kanadasan and Razak (2015). In addition, Table X shows the costing of the above mentioned mix designs. The costing only includes material cost.

It can be seen that the highest price was for conventional SCC with Japanese mix design at RM 481.64 (USD 130.15). Fly ash 40 mix in this research was 65% cheaper than the Japanese mix design and 70% cheaper than the Conventional European mix design. Among the SCC mixes, the fly ash mixes had the lowest price due to the lower sp content used. It can be seen that the SCC can indeed provide a cheaper and more sustainable option for the local construction industry.

3.4 Discussion on Cleaner Production

Besides energy consumption, significant amounts of virgin materials, including limestone and clay, are consumed to produce cement. 1.5 tonnes of virgin materials are needed to produce one ton of cement (Fredrik, 1999). Cement production industries are accountable for about

7% of the world's carbon dioxide discharge and to produce 1 tonne of cement approximately 1 ton of CO_2 is released into the atmosphere (Juan et al., 2011). The palm oil industry contributes to air, river, sea and groundwater pollution in the form of POFA disposal. This study shows that POFA has a good potential as a cement replacement, up to 40% in SCC production. It performs even better when remixed with fly ash. The reuse of agro-industrial waste materials in concrete is an attempt to introduce a sustainable construction material and a cleaner, greener production for the palm oil industry (Rahman et al., 2014).

4. Conclusions

Based on the investigation, the following conclusions could be drawn with regard to using fly ash, POFA and the ternary blend of POFA with fly ash as a replacement for cement in SCC:

- SCC can be produced using POFA, fly ash and the ternary blend of POFA and fly ash without compromising the fresh state properties i.e passing ability, filling ability and segregation resistance.
- the ranges of slump flow diameter and the V-funnel flow time indicate an excellent filling ability of SCC.
- the ranges of difference in height between the concrete inside the bars and that just outside the bars in J-Ring are 5 to 15 mm. POFA mixes performed poorly in comparison with other material in the passing ability tests. However, it performed well when mixed with fly ash and gave a good passing ability.

- the sieve segregation resistance value falls in the range of 1 to 18% indicates a good resistance to segregation.
- all binary and ternary blended samples had lower peak temperatures than the control mix with POFA samples expelling the lowest amount of heat.
- in summary, POFA based SCC was more reliable as a ternary blended mix in terms of workability and heat of hydration.

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TABLE I

CHEMICAL COMPOSITION OF CEMENT, POFA AND FLY ASH

Chemicals	Cement (%)	Fly Ash (%)	POFA (%)
Silicon Dioxide (SiO_2)	20.0	57.8	52.63
Aluminum oxide (Al_2O_3)	5.2	20.0	8.991
Ferric oxide (Fe_2O_3)	3.3	11.7	1.059
Calcium oxide (CaO)	63.2	3.28	3.211
Magnesium oxide (MgO)	0.8	1.95	1.459
Sulphur trioxide (SO_3)	2.4	0.08	-
K_2O	-	3.88	3.133
TiO_2	-	2.02	0.310
Na_2O	-	0.30	0.564
Loss on Ignition	2.5	0.32	27.7

TABLE II

COARSE AGGREGATE GRADATION

Sieve Size (mm)	% Finer than sieve	ASTM requirements (%)
9.5	100	85-100
4.75	5	10-30
2.36	0	0-10

TABLE III

AGGREGATE CHARACTERISTICS SUMMARY

	Material Type	Size Range	Fineness Modulus	Water Absorption	Specific Gravity	Sample
Fine Aggregate	Crushed Quartzite	600µm to 5.0mm	4.29	1.30%	2.67	
	Uncrushed River Sand	0.0µm to 600µm	1.32	1.10%	2.64	
Coarse Aggregate	Crushed Quartzite	5.0mm to 10.0mm		1.40%	2.62	

TABLE IV

FINE AGGREGATE TYPE 1 (CRUSHED QUARTZITE) GRADATION

Sieve Size	% Finer	ASTM requirements for fine aggregates (%)
4.75mm	99	95-100
2.36mm	50	80-100
1.18mm	20	50-85
600µm	2	25-60

TABLE V

FINE AGGREGATE TYPE 2 (RIVER SAND) GRADATION

Sieve Size (µm)	% Finer	ASTM requirements for fine aggregates (%)
600	100	25-60
300	58	5-30
150	10	0-10

TABLE VI

MIX PROPORTIONS AND WORKABILITY TEST RESULTS

-	FLY ASH					TERNARY (POFA & FLY ASH)				POFA			
Percentage Replacement (%)	0 (C)	10	20	30	40	10	20	30	40	10	20	30	40
Water to binder ratio	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.41	0.44	0.44
SP Content (%)	0.86	0.8	0.75	0.66	0.66	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.4
FA(kg/m3)	0	54	108	162	216	27	54	81	108	0	0	0	0
POFA(kg/m3)	0	0	0	0	0	27	54	81	108	54	108	162	216
Cement(kg/m3)	540	486	432	378	324	486	432	378	324	486	432	378	324
0-600μm (Sand)	600	600	600	600	600	600	600	600	600	600	600	600	600
600μm-5mm (Quarry Dust)	550	550	550	550	550	550	550	550	550	550	550	550	550
Course Agg (5-10mm)	400	400	400	400	400	400	400	400	400	400	400	400	400
Slump Flow (mm)	655	660	680	710	760	800	820	755	745	740	700	750	760
T_{500} (secs)	3.71	3.67	3.39	2.9	1.49	2.19	1.82	2.19	2.39	3.19	2.14	2.48	2.28
J-Ring Diameter (mm)	550	600	600	630	640	750	760	700	690	710	600	720	710
Step Height (mm)	10	10	10	12	12	5	8	8	8	10	15	9	7
V-Funnel Flow Time (secs)	11.48	9.33	9.10	8.32	5.52	9.13	9.98	8.56	10.12	12.48	10.68	7.19	7.19
Segregation Index (%)	9	8	4	13	18	12	13	10	6	13	1	6	10

TABLE VII

PERFORMANCE CRITERIA FOR WORKABILITY OF SCC [EGSCC]

Property	Class				
Filling ability	SF1	Slump flow	550~650		
	SF2		660~750		
	SF3		760~850		
	VS1/VF1	T500 (s)	≤ 2	V-funnel time (s)	≤ 8
	VS2/VF2		≥ 2		9~25
Passing ability	PA1	Step height in J-ring (mm)	Sj ≤15 (59 mm bar spacing)		
	PA2		Sj ≤15 (40 mm bar spacing)		

Segregation resistance	SR1	Sieve segregation (%)	⩽20
	SR2		⩽15

TABLE VIII

SUMMARY OF EVALUATION OF HEAT TEST RESULTS

Description	Control	Fly Ash 30	Fly Ash 40	Ternary 30	Ternary 40	POFA 30	POFA 40
Initial Temperature(°C)	29.7	29.8	30.1	30.1	30.8	31.4	31.4
Peak Temperature (°C)	74.3	65.2	59.2	64.1	58.4	63.1	57.9
Time at Peak Temperature (hrs)	14	20.5	21.0	18.0	18.5	17.5	19.0

TABLE IX

PRICING AND MIX DESIGN COMPARISON FOR AGRO-INDUSTRIAL SCC

Materials	Cost (per kg)	This Research kg/m^3	Conventional SCC (Japan)* kg/m^3	Conventional SCC (Europe)** kg/m^3
Cement	RM 0.44	324 – 378	530	470
Gravel/Crushed Quartzite	RM 0.06	950	789	777
Sand	RM 0.08	600	751	790
Fly ash	RM 0.15	108 – 216	70	-
POFA	RM 0.15	108 – 216	-	-
Limestone filler	RM 0.40	-	-	133
Ground granulated blast-furnace slag (GGBS)	RM 0.03	-	61	-
SP	RM 15.28	3.56 – 7.56	8.8	4.75

TABLE X

COMPARISON OF COSTING FOR AGRO-INDUSTRIAL SCC

Materials	POFA30 (kg/m^3)	POFA40 (kg/m^3)	Fly Ash 30 (kg/m^3)	Fly Ash 40 (kg/m^3)	Ternary 30 (kg/m^3)	Ternary 40 (kg/m^3)	Conventional SCC (Japan) (kg/m^3)	Conventional SCC (Europe) (kg/m^3)
Cement	133.06	99.792	166.32	124.74	166.32	124.74	233.2	206.8
Gravel	52.25	52.25	52.25	52.25	52.25	52.25	43.395	42.735
Sand	48	48	48	48	48	48	60.08	63.2
Fly ash	0	0	24.3	32.4	12.15	16.2	10.5	0
POFA	24.3	32.4	0	0	12.15	16.2	0	0
Limestone filler	0	0	0	0	0	0	0	53.2
GGBS	0	0	0	0	0	0	0	0
SP	99.014	115.52	54.46	54.46	90.76	90.76	134.464	72.58
TOTAL	356.62	347.96	345.33	311.85	381.63	348.16	481.64	438.52

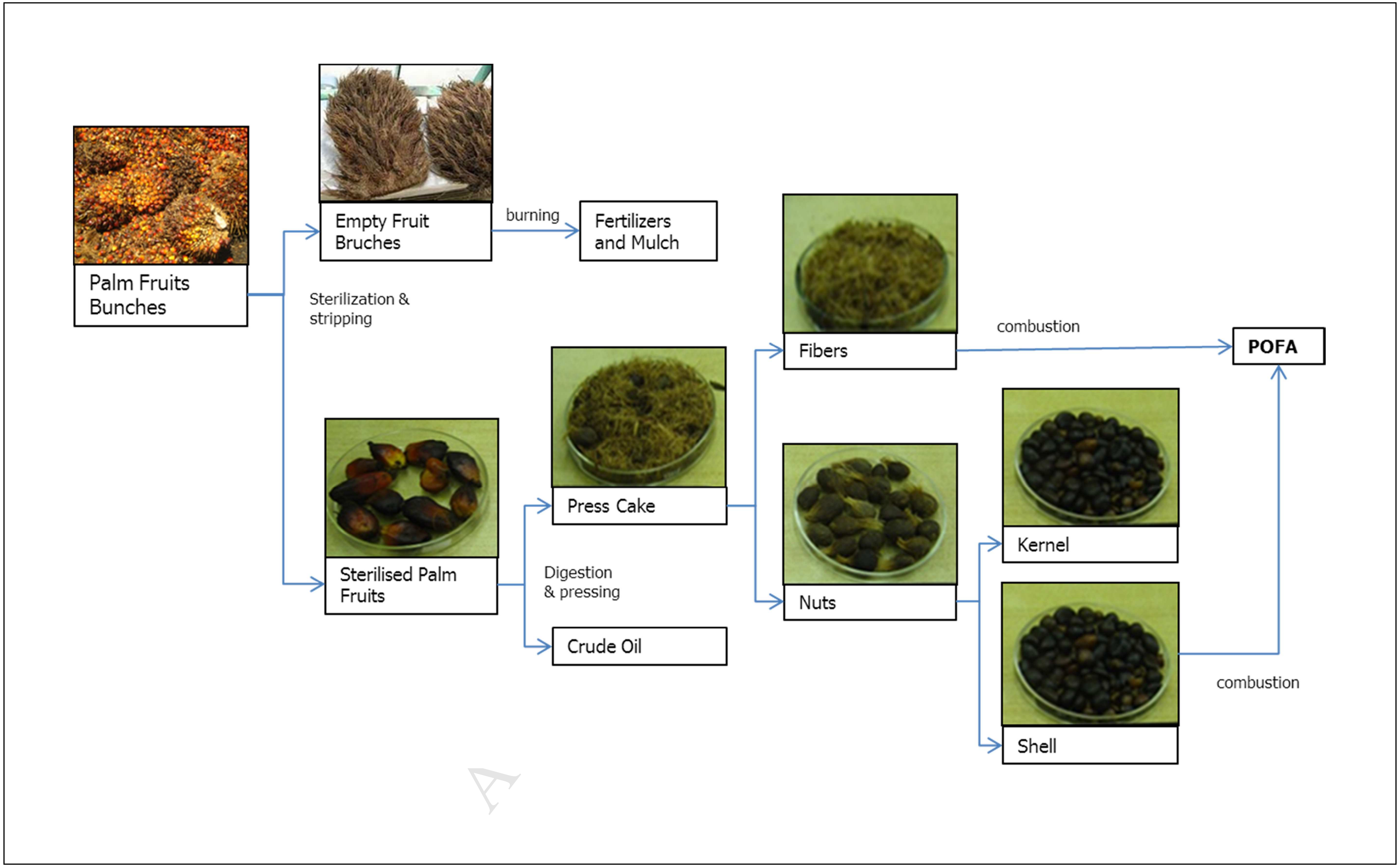

Fig. 1: The Schematic Diagram for Palm Oil Processing & POFA Production

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Fig. 2: Solid waste in palm oil mill

Fig. 3: POFA collected from the chimney

Fig. 4: POFA at the bottom of the furnace

Fig. 5: Heat of hydration test set-up

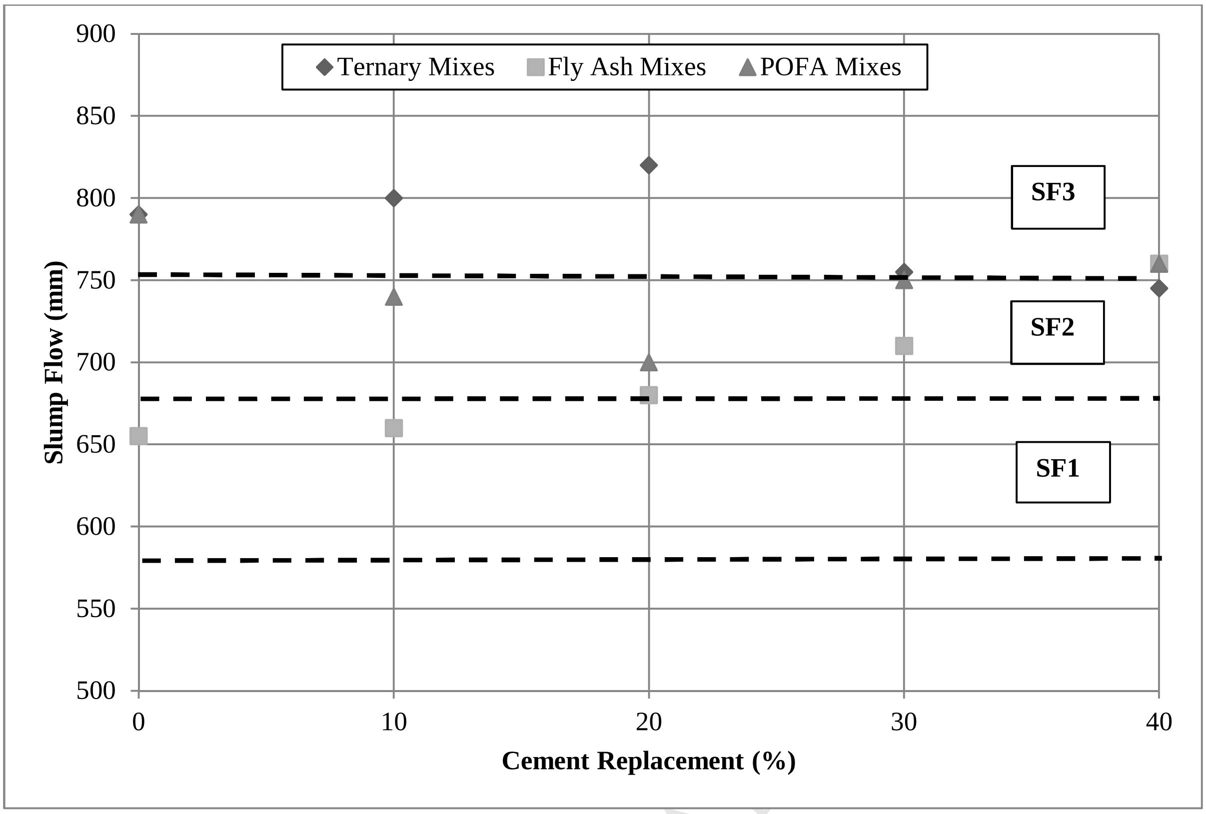

Fig. 6: Comparison of Slump Flow for Fly Ash, POFA and Ternary Blend.

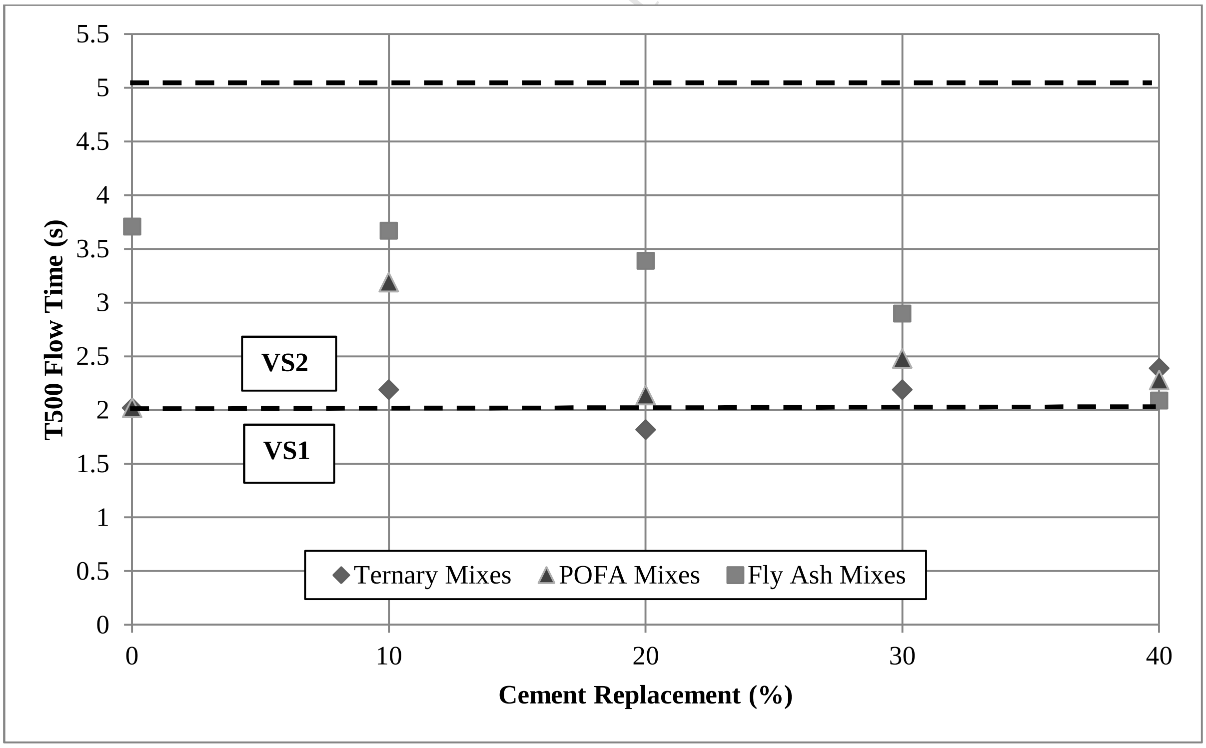

Fig. 7: Comparison of T_{500} Flow Time for Fly Ash, POFA and Ternary Blend.

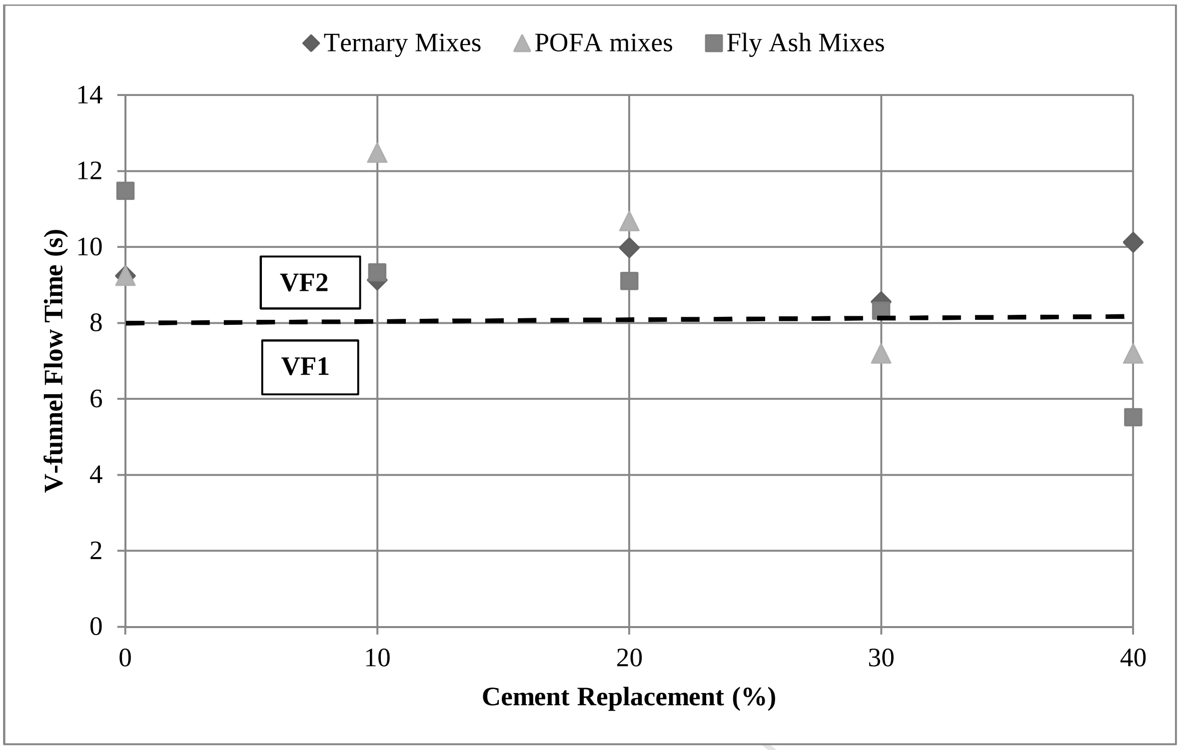

Fig. 8: Comparison of V-funnel Flow Time for Fly Ash, POFA and Ternary Blend.

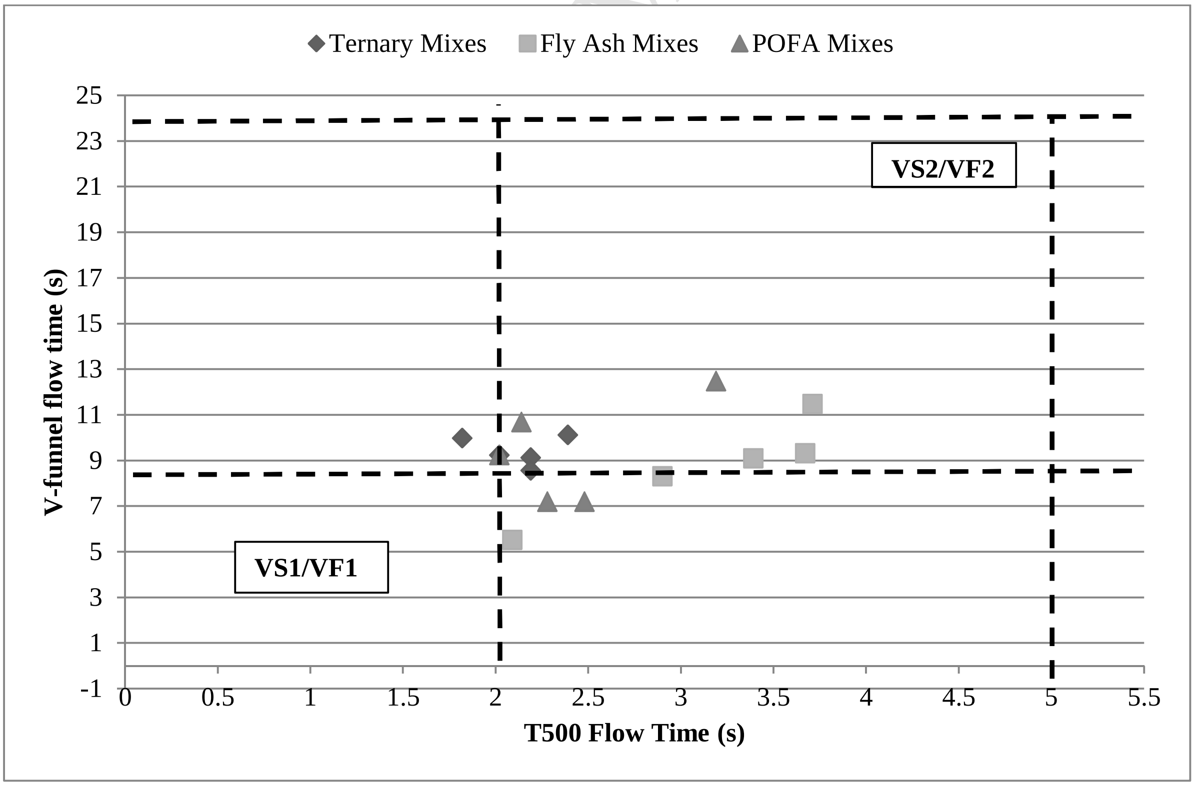

Fig. 9: Variation of viscosity classes with T500 and V-funnel flow times.

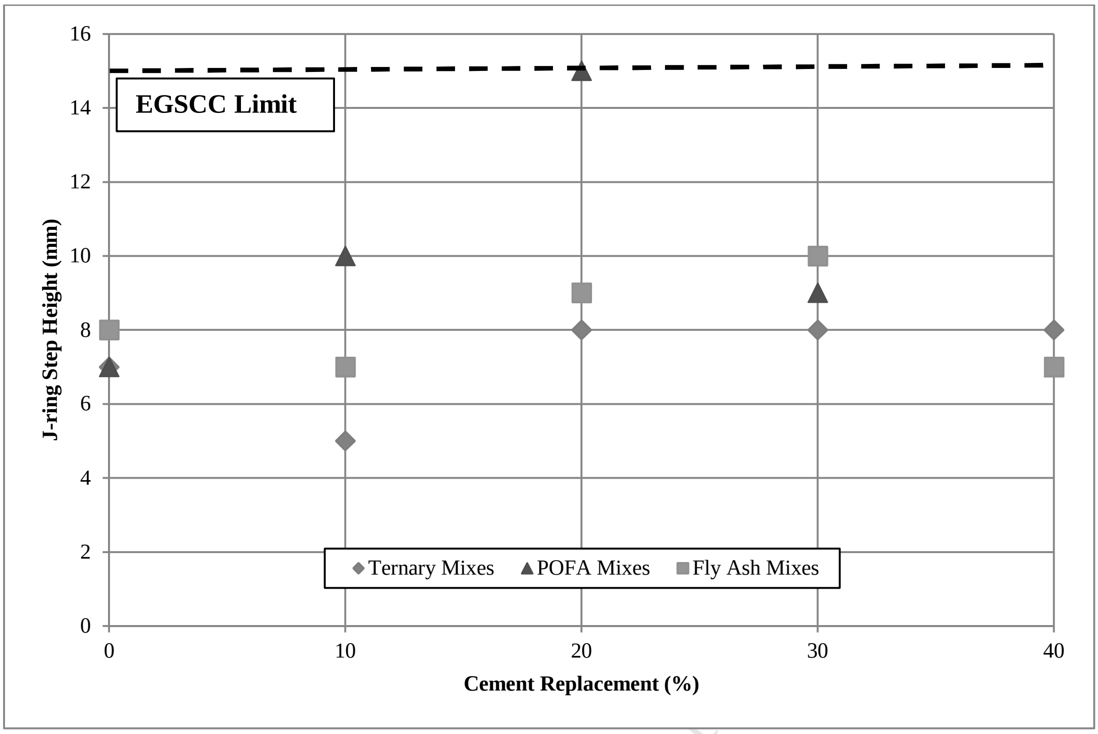

Fig. 10: Comparison of J-ring Step Height for Fly Ash, POFA and Ternary Blend.

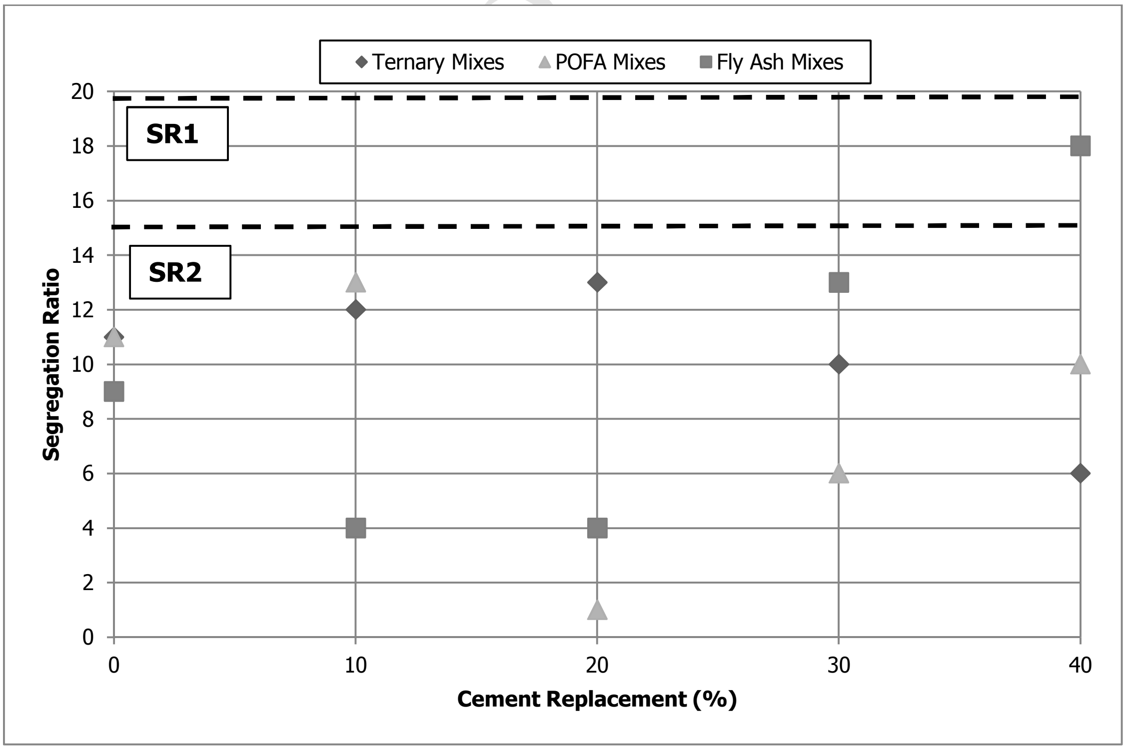

Fig. 11: Comparison of Segregation Ratio for Fly Ash, POFA and Ternary Blend.

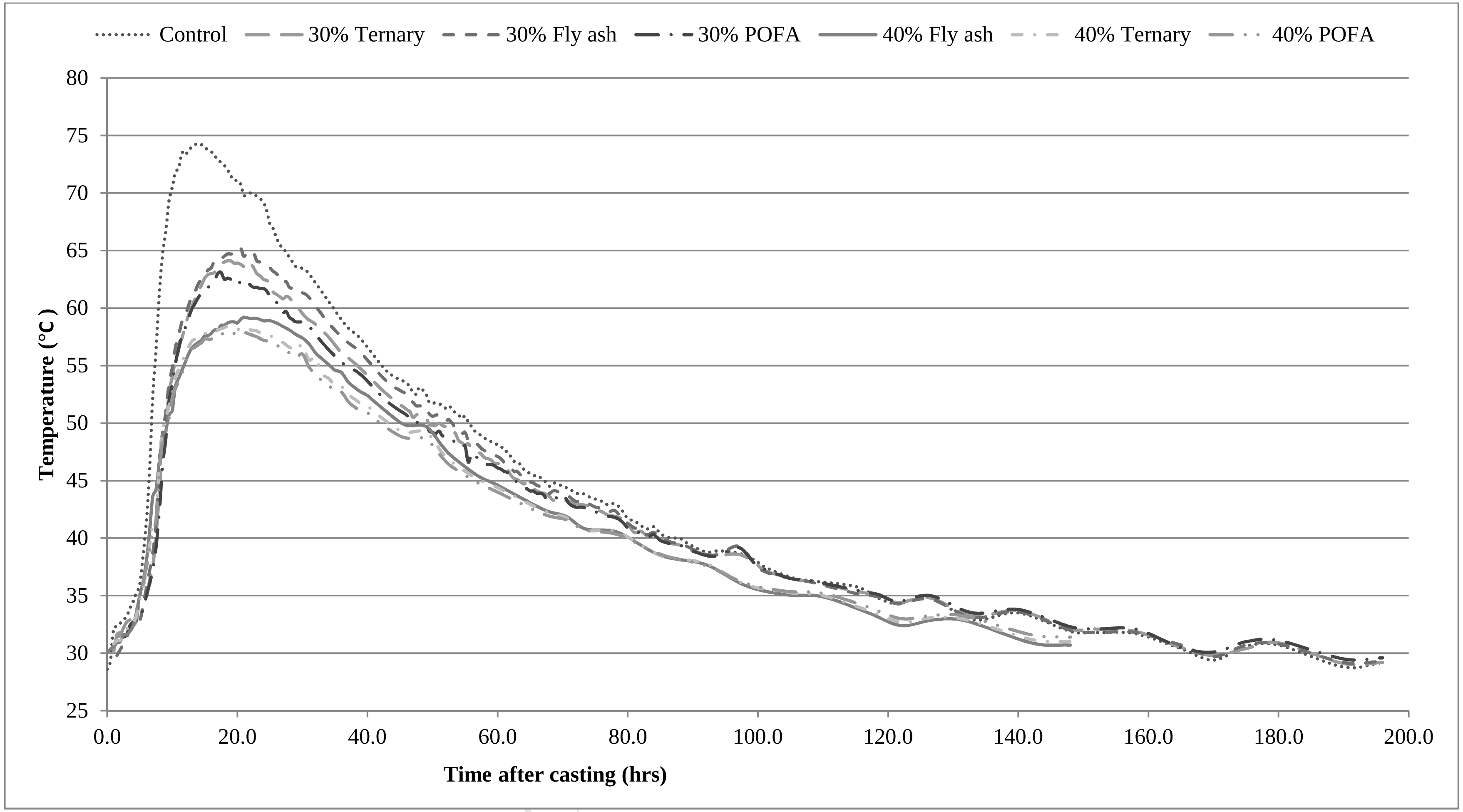

Fig. 12: Heat of hydration for all mixes

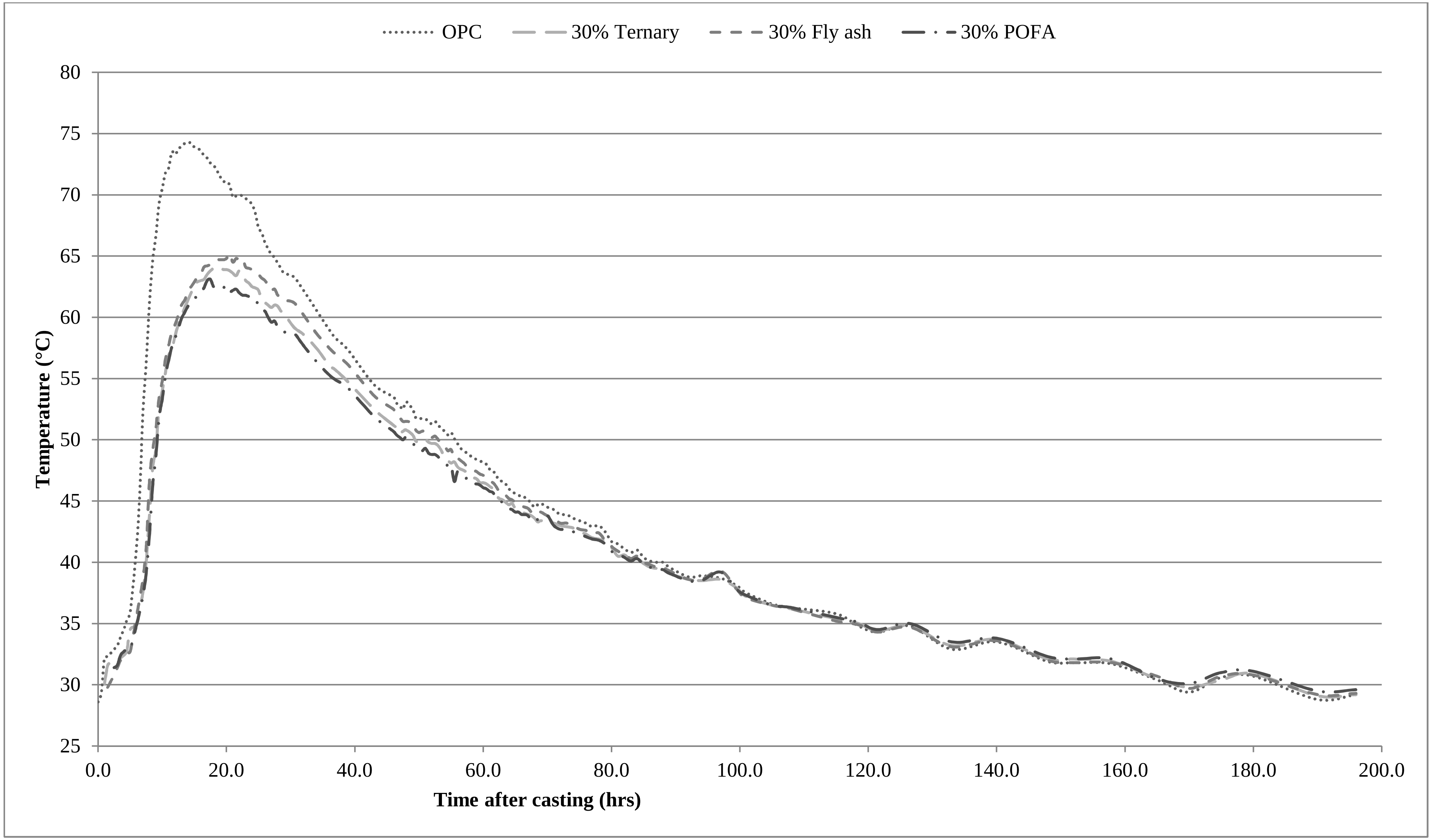

Fig. 13: Heat of hydration of Control and 30% blended concrete.

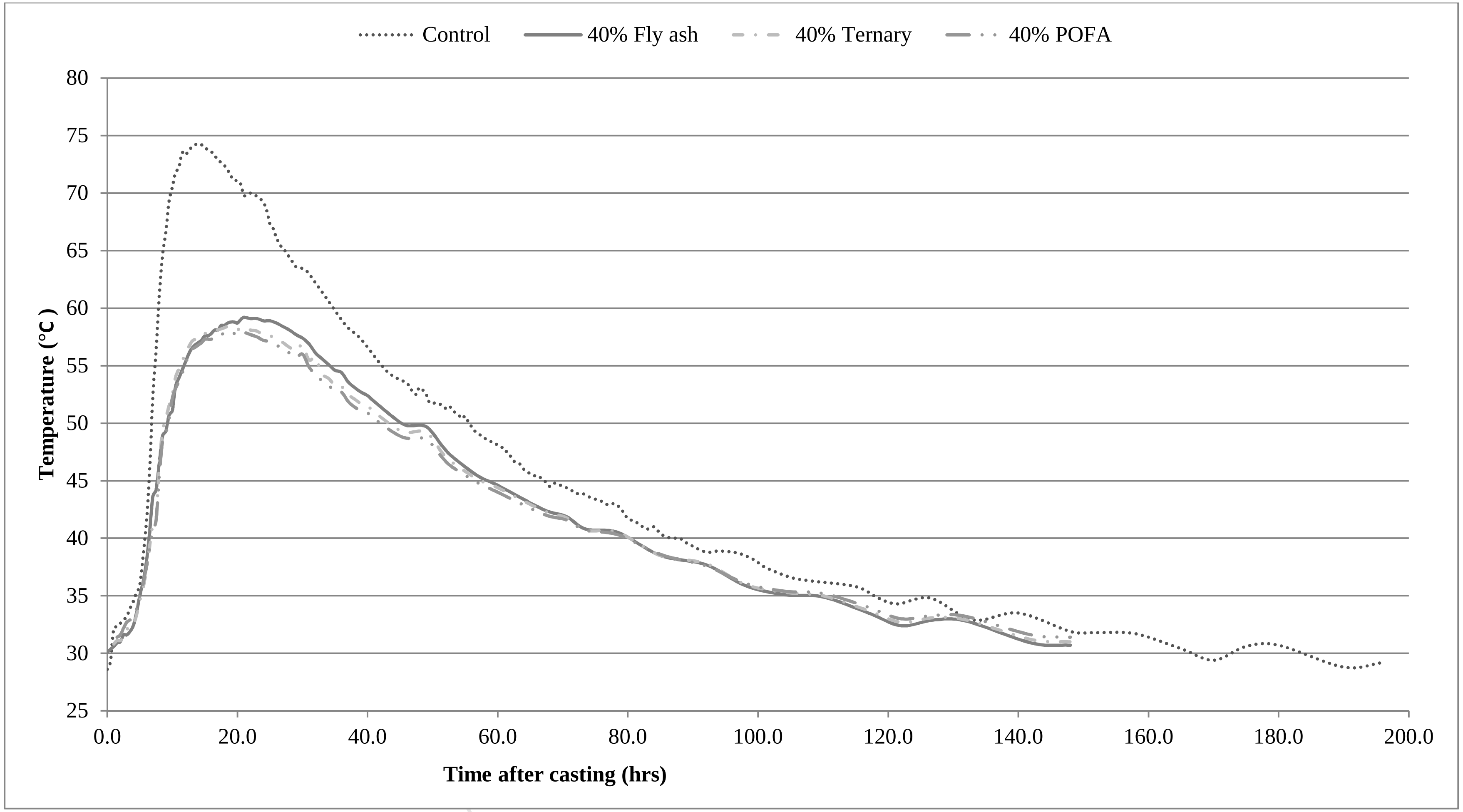

Fig. 14: Heat of hydration of Control and 40% blended concrete.

Highlights:

- POFA, fly ash and blended POFA and fly ash was used to develop SCC.
- All mixes satisfied the European Guidelines for fresh state properties of SCC and workability properties of POFA SCC improved when fly ash is added as ternary blended mixes.
- All binary and ternary blended samples had lower peak temperatures than the control mix.