# THE INFLUENCE OF FLY ASH ON THE RELATIONSHIP BETWEEN AUTOGENOUS SHRINKAGE AND HYDRATION HEAT IN HIGH-PERFORMANCE CONCRETE
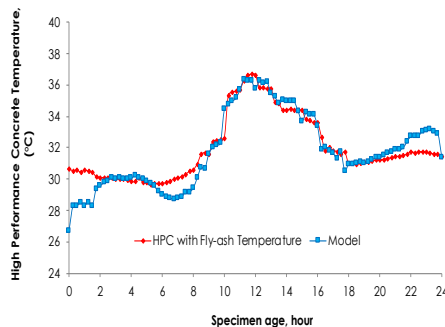
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## Graphical abstract



## Abstract

Autogenous shrinkage and heat of hydration are causes of premature cracking in HPC. Making high-performance concrete that has no cracks is a challenge. This research looks at the causes of these premature cracks and the impact of fly ash on these cracks. Observations were made on samples measuring 15 cm × 15 cm × 60 cm, 3 for HPC, and 3 for HPCfa with fc' 60 MPa. HPCfa is HPC where 10% of the binder is fly ash. One embedded strain gauge was installed on each sample at a distance of 5 cm from the sample. After the concrete was poured, the samples were covered with styrofoam for 24 hours and observations were made every 15 minutes. Data from 3 samples were processed using Dixon's criteria. The results showed that fly ash delays the peak heat of hydration by 4 hours, shortening the peak shrinkage duration to 30%, with a shrinkage value of 57% compared to HPC. Slowing down the occurrence of hydration peaks makes the concrete bond stronger so that it is more resistant to withstanding shrinkage peaks. The greatly reduced peak shrinkage duration means that the period of maximum suffering in young concrete is also shorter. The absence of fly ash means that the peak shrinkage does not immediately decrease because there is no osmotic pressure. Fly ash affects a hydration heat pattern similar to autogenous shrinkage ($\varepsilon_t$). Both have a linear relationship $H_t = 357216\ \varepsilon_t + C$. The HPC similarity only reaches the peak of hydration.

*Keywords*: Autogenous shrinkage, concrete, fly ash, high-performance concrete, hydration heat

## 1.0 INTRODUCTION

High-performance concrete (HPC) is being increasingly utilized due to its high compressive strength and water resistance. However, a significant challenge associated with its application is the propensity for premature cracking. Autogenous shrinkage in high-performance concrete (HPC) blocks with Ordinary Portland Cement (OPC) is approximately 225 times that of normal concrete blocks with Portland Cement Concrete (PCC) [1]. While this value may seem relatively small when compared to long-term shrinkage, it is notably substantial when contrasted with the shrinkage observed in normal concrete.

Because High-Performance Concrete (HPC) can only be produced with a low water-to-cement ratio (w/c), there is a potential risk of late ettringite formation, leading to concrete expansion after the plastic phase has concluded. This development stress

has the potential to fracture the weaker concrete bonds. The constrained use of water makes the mixing and casting of HPC challenging, posing a risk of generating numerous voids. To address this challenge, additives such as High-Range Water Reducer (HRWR) are employed.

The impact of HRWR on compressive strength does not exhibit regularity, introducing variability to the hydration process. Jabbar *et al.*, 2021 [2], conducted a study on the hydration process of ultra-high-performance concrete. The initial twenty-four hours represent a period where the hydration process occurs at a rapid rate. To ensure that the hydration process unfolds without external influence, the sample is enclosed, ensuring that any observed behavior stems purely from the hydration process or internal factors within the concrete. The resulting deformation is known as autogenous shrinkage [3]. This 24-hour duration aligns with the ASTM C1608 recommendation for the minimum testing time [4].

The shift in cement used for High-Performance Concrete (HPC) production has transitioned from Ordinary Portland Cement (OPC) to Portland Pozzolan Cement (PPC) or Portland Composite Cement (PCC). This shift is driven by the need to reduce carbon dioxide ($CO_2$) gas emissions, a significant contributor to global warming. Cement production is a major contributor to this issue, leading to restrictions on OPC production. One strategy to mitigate greenhouse gas emissions involves replacing some of the clinker in cement systems with limestone [5].

Another approach is the substitution of some clinker with fly ash, a pozzolanic material that results in the production of PPC. Additionally, replacing some clinker with both fly ash and blast furnace slag produces PCC. Consequently, fly ash is incorporated into both PPC and PCC formulations. Notably, fly ash finds application in geopolymer concrete as well [6, 7].

As mentioned earlier, the presence of fly ash in a concrete mixture does not eliminate the visibility of autogenous shrinkage [8]. Nevertheless, due to the increasing prevalence of fly ash usage, there is a growing need for a comprehensive examination of its effects on concrete. Numerous researchers are directing their attention to concrete compositions incorporating fly ash.

Fly ash has demonstrated its ability to mitigate autogenous shrinkage in cement paste [9, 10], and in geopolymer concrete [6,7]. Other researchers stated that apart from reducing autogenous shrinkage, fly ash can also reduce the heat of hydration in slabs [11], However, it is essential to be cautious, as an increased fly ash content may elevate the risk of drying. The optimal fly ash content is ±30% by weight of cement [11]. Notably, published studies on the autogenous shrinkage of fly ash and ground-granulated blast furnace slag concrete have shown that the overall autogenous shrinkage of fly ash concrete is comparable to that of reference concrete [12].

Furthermore, fly ash and alkali-activated slag exhibit significant autogenous shrinkage [13]. Conversely, High-Performance Concrete (HPC) with Self-Compacting Concrete (SCC) containing a high proportion of ground ash admixture experiences significantly less autogenous shrinkage [14]. It is worth noting that calcined lime clay hydrates more rapidly than fly ash, leading to greater autogenous shrinkage [10].

As soon as concrete comes into contact with water, a chemical reaction occurs. This chemical reaction dominates the behavior of the concrete during the first 24 hours. The primary features of chemical reactions include temperature and physical changes, making them key parameters for early-age evaluation. Given that the fundamental characteristic of a chemical reaction is temperature variation, even a slight shift indicates an alteration in the chemical process, leading to changes in form and volume.

During this period, chemical energy is generated through the decomposition and formation of compounds. The initial chemical reaction involves the release of heat energy, resulting in the rapid movement of particles. Consequently, there exists a correlation between the heat of hydration and particle movement. The movement of particles induced by the heat of hydration and chemical energy leads to the expansion and contraction of concrete. This process occurs swiftly and exhibits significant fluctuations.

The heat of hydration at any given time ($H_t$) is a measure of the heat produced per unit mass of anhydrous compounds that have undergone reaction. $H_t$ stands as the primary factor detrimental to concrete at an early age [15]. However, even with the use of low hydration heat in High-Performance Concrete (HPC), along with fly ash or shrinkage-reducing materials, autogenous shrinkage remains more apparent in HPC [8]. This observable shrinkage is termed macroscopic volume change [3]. The rates of hydration heating and autogenous shrinkage are closely interconnected [16]. Consequently, several researchers have explored methods to reduce the heat of hydration in concrete.

The reduction of heat of hydration can be addressed by incorporating coarse fly ash [17], GBA-FA [14], fly ash-slag cement ternary mixtures [18]), Portland Lime Cement (PLC), and OPC + limestone (LS) paste, as well as PLC and OPC + LS with slag, as comparable alternatives [5]. Heat can change materials [19] meaning changing their behavior or deformation. Notably, it has been documented that the historical pattern of autogenous shrinkage closely mirrors the historical pattern of hydration temperature at an early age [16].

As the utilization of fly ash increases, its interaction with cement concrete, which is susceptible to the development of premature cracks, necessitates exploration. If the applied mixture and treatment render High-Performance Concrete (HPC) capable of accommodating expansion and shrinkage

resulting from hydration reactions, the occurrence of premature cracking can be mitigated. Conversely, without proper treatment, the concrete is prone to cracking [8]. Premature cracking can have serious consequences because it can accumulate and lead to structural destruction. The behavior exhibited by concrete in its early stages significantly influences its long-term performance [20].

Creating high-performance concrete resistant to crack-inducing forces poses a significant challenge. Addressing this challenge necessitates a comprehensive understanding of the factors contributing to autogenous cracks. Without a clear understanding of the root causes, preventing premature cracking in High-Performance Concrete (HPC) will not be effective. There is a need to explore the mechanisms operating in concrete from its early stages, extending to the casting process.

## 2.0 MATERIAL AND METHOD

The research was conducted within the initial 24 hours, during which chemical reactions play a dominant role in behavior. The primary feature of a chemical reaction is the alteration in temperature and physical properties. Fly ash is recognized for its ability to mitigate shrinkage in concrete. Given that temperature changes are a key characteristic of chemical reactions, it is imperative to delve deeper into the temperature sensitivity associated with premature deformation in concrete containing fly ash. This exploration aims to identify alternatives for producing High-Performance Concrete (HPC) that mitigates the risk of premature cracking.

### Materials

The research was conducted experimentally. The materials used are HPC and HPC with 10% fly ash by weight of binder (HPCfa). The samples were made into beam of 150 mm × 150 mm × 600 mm 3 pieces for HPC and 3 pieces for HPCfa.

The material properties used are presented in Table 1 and the mix design in Table 2.

**Table 1** Material Properties

| Properties | High-performance Concrete with and without fly-ash | |
|---|---|---|
| Mix design | ACI 211.4R 1993 [21] | |
| Sand | Sungai Liat Bangka, Sumatra | |
| Specific gravity | 2.605 | |
| Absorption | 0.4% | |
| Coarse Aggregate | Banten, West Java | |
| Size (mm) | 70%: 13-19 | 30%: 6-12 |
| Specific gravity | 2.563 | 2.636 |
| Absorption | 1.543% | 2.26% |
| Cement | OPC Indocement | |
| High range water reducer | Viscocrete 10 Sika | |

**Table 2** Mix design

| Materials | HPC | HPCfa |
|---|---|---|
| Cement (kg/m$^3$) | 500 | 454.3 |
| Silica fume | 40 | 40 |
| Fly-ash | | 57.14 |
| Fine Aggregate (kg/m$^3$) | 800 | 800 |
| Coarse Aggregate (kg/m$^3$) | 935 | 935 |
| HRWR | 7.6 | 7.6 |
| Water (kg/m$^3$) | 142.6 | 146 |
| W/Cm | 0.264 | 0.264 |

The cement quantity is set at 500 kg/m3 to align with the correction factor of 1 (22). To prevent brittle failure, the silica fume content is limited to 8%, which is below the threshold of 10% of the cement weight. For optimal density, two sizes of coarse aggregate are selected. Additionally, the High-Range Water Reducing (HRWR) admixture is formulated at 1.52%, staying below the prescribed maximum limit of 2%.

### Method

HPC has a compressive strength of 60 MPa and, a slump flow of 35 ± 2 cm (Figure 1a). Shrinkage was measured as strain change against time by installing one EVWSG in each specimen (Figures 1b and 1c). The EVWSG can detect strains up to 3000 μm with an accuracy of about 0.025% and concrete temperatures between -80°C and 60°C with about 5% accuracy.
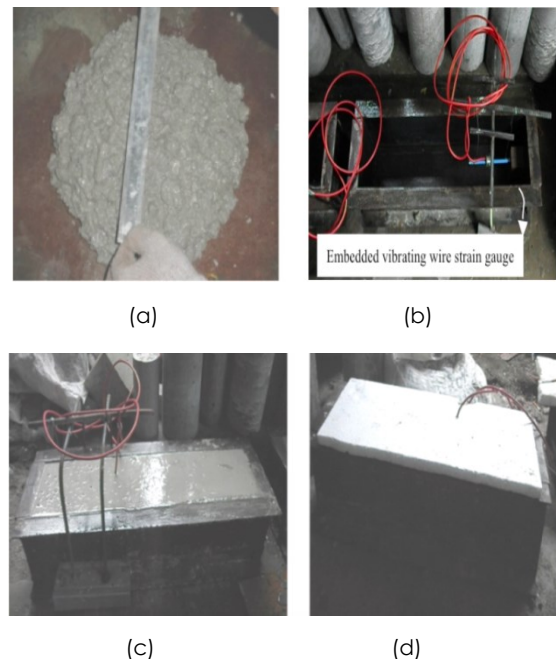


**Figure 1** (a) Slump flow, (b) Installation of vibrating wire embedded strain gauge, (c) Concrete with strain gauge, (d) Covering the sample with styrofoam

Autogenous conditions were approached right after casting, the specimens were covered by styrofoam to eliminate the water evaporation and maintain heat in the concrete (Figure 1d). Covering with styrofoam was also chosen because this method is easy to apply to real beams. Observation was performed right after pouring as follows: 0–24 hours, every 15 minutes using a read-out.

The results of the deformation readings are processed by taking into account differences in concrete expansion and strain gauges as well as tool calibration. Data from the three specimens in each group were processed by the outlying test using the Dixon criteria. HPC and HPCfa strain and temperature data are averages of the received data. The research flow chart is presented in Figure 2.
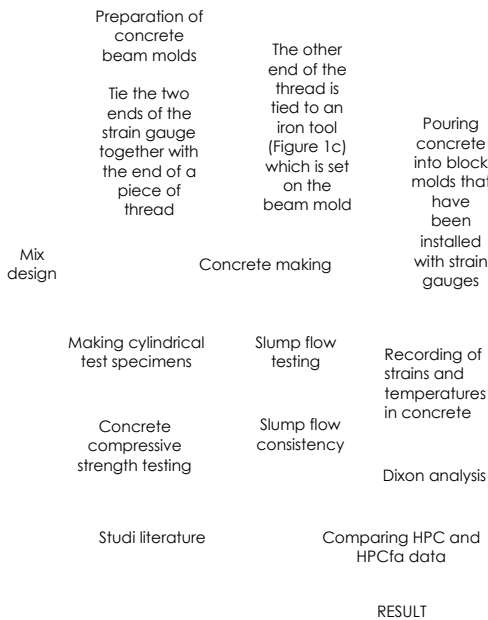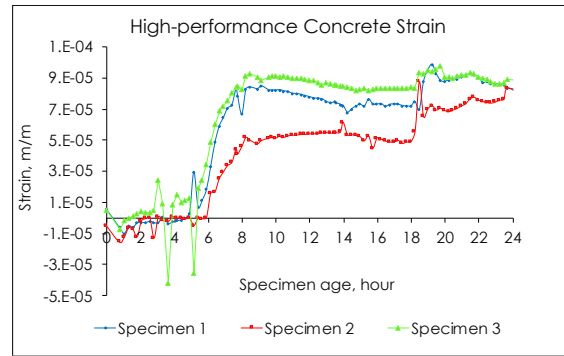
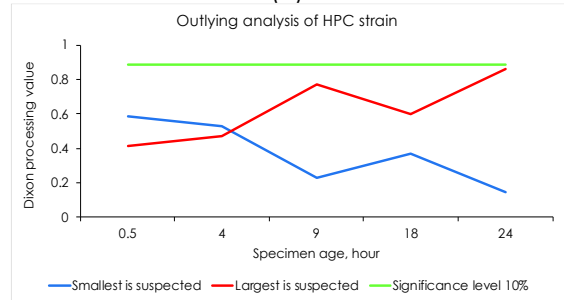**Figure 2** Research methodology flow chart

There is the same pattern of autogenous shrinkage and hydration heat in the three HPC specimens (Figures 2a and 2c) and the three HPCfa samples (Figures 3a and 3c).
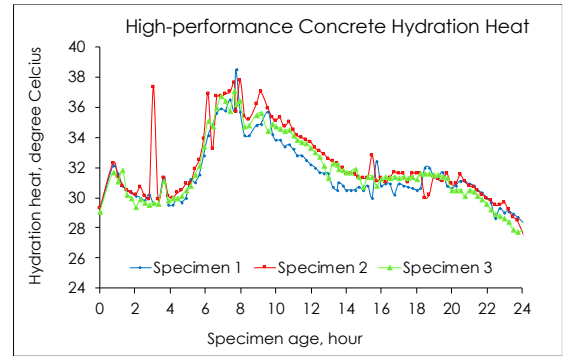
**Data Processing**

The results of outlying processing with Dixon criteria according to ASTM E178-02 [23] for the three specimens are presented in Figures 3 and 4.
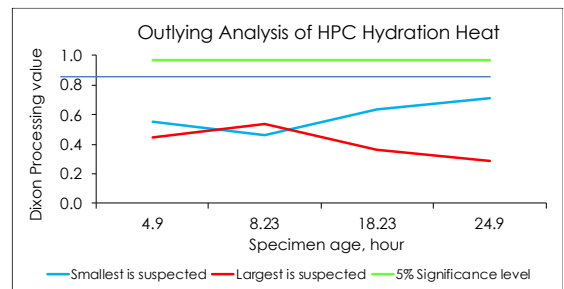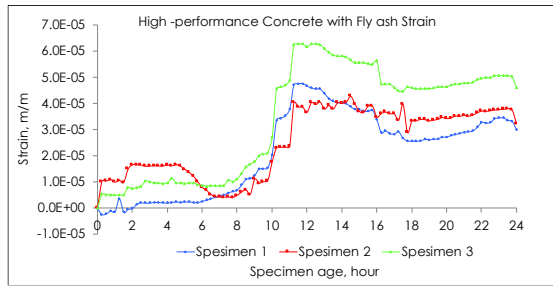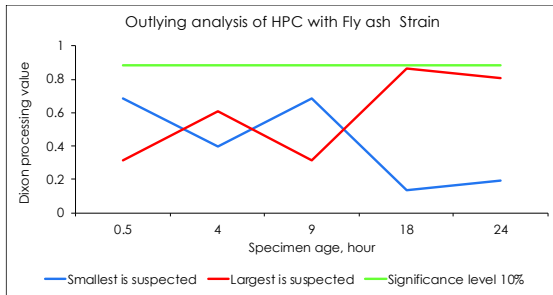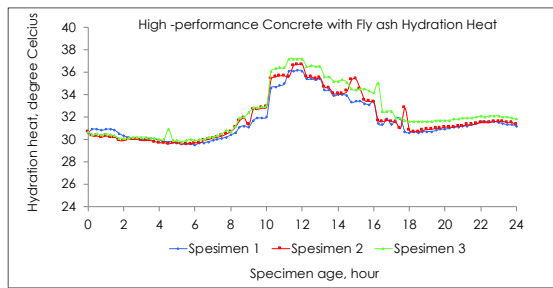
(a)

(b)

( c )

(d)

**Figure 3** Strain, hydration heat, and its outlying analysis of HPC: (a) Strain data, (b) Outlying analysis of strain data, (c) Hydration heat data, (d) Outlying analysis of hydration data

(a)



(b)



( c )



(d)

**Figure 4** Strain, hydration heat, and its outlying analysis of HPCfa: (a) Strain data, (b) Outlying analysis of strain data, (c) Hydration heat data, (d) Outlying analysis of hydration data
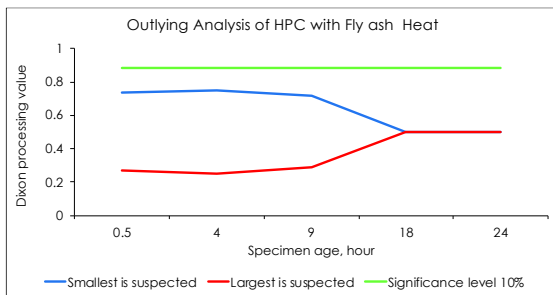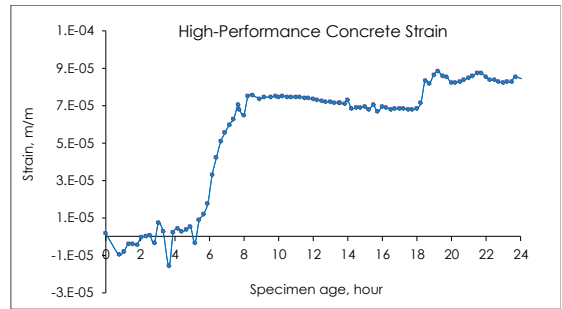
## Autogenous Shrinkage and Hydration Heat

From the outlying analysis (Figure 3 and Figure 4) it can be said that all data is accepted, so autogenous shrinkage and hydration heat are taken from the average of all data and presented in Figure 5.



(a)
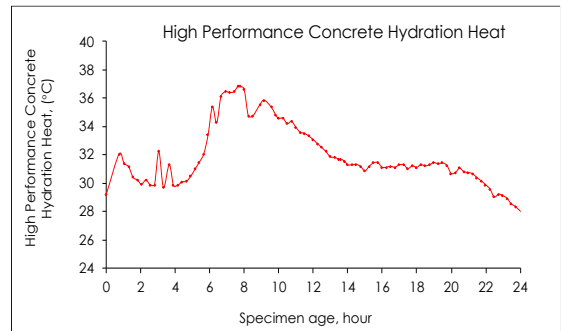


(b)



(c)



(d)

**Figure 5** Autogenous shrinkage and hydration heat: (a) Strain of HPC, (b) Hydration heat of HPC, (c) Strain of HPCfa, (d) Hydration heat of HPCfa

## RESULT

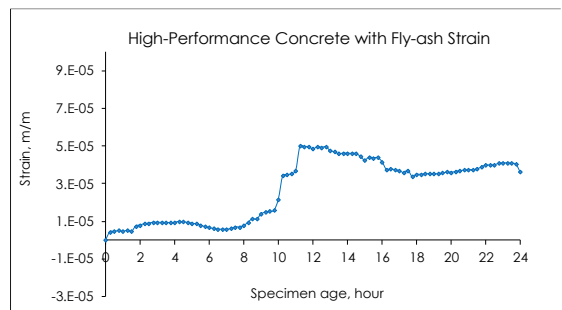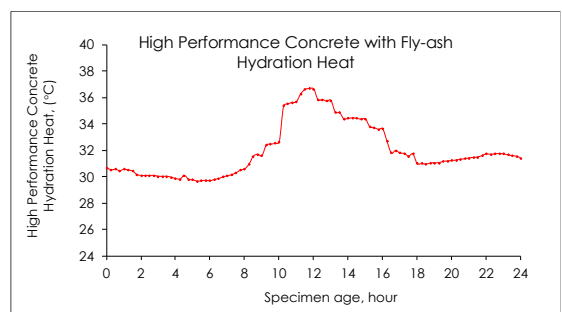Replacement of 10% by weight of binder with high calcium class F fly ash caused a significant change in the autogenous shrinkage pattern. The autogenous shrinkage strain pattern in HPCfa follows the heat of hydration pattern; whereas HPC does not follow the hydration heat pattern, especially after the peak hydration heat.

There are 2 autogenous shrinkage peaks in HPC. The first maximum autogenous shrinkage in HPC occurred at 8 hours and the second maximum was at 19.23 hours. The second peak of autogenous shrinkage is higher than the first peak, at 8.829E-05. The peak heat of hydration occurs at 8 hours with a temperature of 37°C.

There was 1 peak of autogenous shrinkage in HPCfa which occurred at the 11th hour at 5,033 E-05.The heat of hydration peak occurred at the 12th hour with a temperature of 36.8°C.

Maximum autogenous shrinkage of HPCfa occurs slower ±in 3 hours compared to HPC. The maximum HPCfa shrinkage is 57% HPC.

There is a close relationship between autogenous shrinkage and its heat of hydration in HPCfa. There are four stages in autogenous deformation. The first stage in HPCfa is the initial $C_3S$ and $C_3A$ reaction which appears as a low deformation with a relatively stable rate, the second stage is Dormancy, the third stage is a high rate of shrinkage, and the fourth stage is a high rate of expansion. The close relationship between heat hydration and autogenous shrinkage can be expressed by Equations 1, 2, and 3 which describe stage 2, 3, and 4 of HPCfa.

Hydration heat in 2-10 hours:
$$H_{h2-10}= 357216\ \varepsilon_t + 26.7 \tag{1}$$
Hydration heat in 10.25-11.00 hours:
$$H_{h\ 11.25-11} = 357216\ \varepsilon_t + 22.6 \tag{2}$$
Hydration heat in 11-24 hours:
$$H_{h11-24}= 357216\ \varepsilon_t + 18.5 \tag{3}$$

Where $\varepsilon_t$ is strain at time t

All slopes in the three equations have the same value, only the constants are different (Equations 1, 2, 3). The same slope also shows the same amplification value of autogenous shrinkage at the three stages against autogenous shrinkage at time t. The mathematical model and experimental result are presented in Figure 5a. The model has an average deviation of 2% (Figure 6 b).
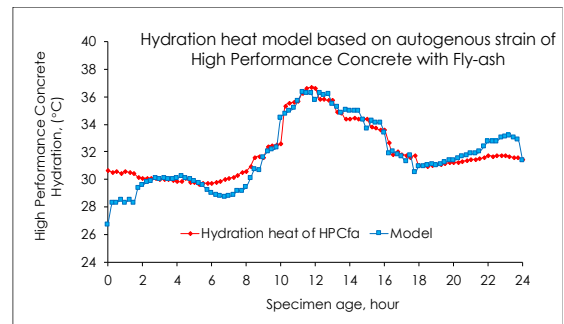


(a)
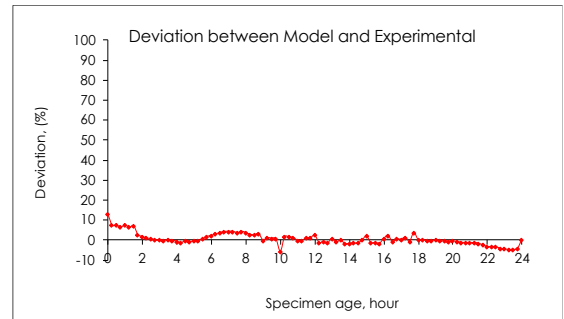


(b)

**Figure 6** (a) Hydration heat model based on autogenous shrinkage, (b) Deviation between experimental and model

## 4.0 CONCLUSION

In conclusion, when using archival tissues, modifying the IHC staining variables such as antigen retrieval conditions i.e. pH and temperature, primary antibody concentration and incubation period improves staining for the MMR, BRAFV600E, and FOXP3 proteins. Unfortunately, the different options for the aforementioned IHC staining variables appear to be limitless. A comparison of the two antigen retrieval methods, heat-induced epitope retrieval (HIER) and proteolytic-induced epitope retrieval (PIER), choosing the appropriate blocking solution and antibody diluent, and secondary antibody for the IHC detection signal are additional aspects of IHC optimization that are not covered in our study. Researchers frequently employ TBS as a diluent, however the choice of diluent can significantly affect how well an antibody performs. Similarly, the detecting technique used might have a considerable influence on staining quality. Even though HRP secondary antibodies generate an improved signal and clearer background, more concentration modification is probably required to improve the IHC outcomes. Above all, even the effort took a few weeks to validate antibody specificity and enhance the staining process, we learned that our optimisation work was certainly worthwhile for our study and to direct future IHC research pertaining to the relevant antibodies.

## DISCUSSION

The chemical shrinkage of cement paste was decided by its chemical composition.
Ultimate chemical shrinkage:

$$CS_{Ultimate} = 0.0704\,[C_3S] + 0.0724\,[C_2S] + 0.117[C_4AF] + 0.171[C_3A] \quad (4)$$

Values in the brackets percentage of the composition of certain minerals and the coefficient in front have a unit of ml/g. The coefficients are very sensitive to values chosen for the densities of the different composition phases, which resulted in a difference between researchers [24]. However, there are several complications behind this equation. The coefficients change if assuming different hydration conditions, which could be confusing.

Both HPCs have the same w/cm, namely 0.264. This w/cm value was chosen because, in the range of w/cm values 0.3 – 0.26, there was only a slight change in the composition of the C-S-H gel [25]. From Equation 4, It can be seen that the coefficient of $C_3A$ is the largest in ultimate chemical shrinkage followed by $C_4AF$. During the first 24 hours, the water used for the hydration and pozzolanic reactions was the water that was mixed because the specimen was covered in styrofoam.

### Autogenous Shrinkage Delay in HPCfa

The replacement of 10% of cement with fly ash resulted in a notable shift of the peak shrinkage and peak hydration heat in HPCfa, occurring approximately ±3 hours later or at 12 hours of age (refer to Figure 4 a, b, c, d). By the age of 12 hours, fly ash balls began forming, featuring a double layer of Ca(OH)2 that enhances the strength of this hydration product [26]. Ettringite at this stage undergoes a transformation from grains to needles, penetrating the cement core [27]. This strengthens the hydration product.

The pozzolanic reaction of fly ash awaits Calcium Hydroxide (CH), which is a hydration product of $C_3S$ and $C_2S$. The aluminosilicate pozzolan reaction in fly ash progresses more slowly than the hydration of $C_3S$ and approaches the rate of hydration of $C_2S$. Notably, this fly ash contains 21.49% $Al_2O_3$ aluminate, in contrast to the 3.7% found in Ordinary Portland Cement (OPC). The Al2O3 content in High-Performance Concrete (HPC) was 3.45%, while in HPCfa, it stands at 5.29% (refer to Table 3). This variance contributes to the occurrence of shrinkage peaks.
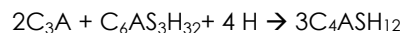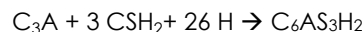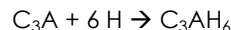
**Tabel 3** Chemical content of the binder

| Chemical element | OPC | Silica fume | Fly ash | HPC | HPCfa |
|---|---|---|---|---|---|
| MgO | 1.0 | | 1.0 | 0.9 | 0.9 |
| $Al_2O_3$ | 3,7 | | 21.49 | 3.45 | 5.29 |
| $SiO_2$ | 13.7 | 97.7 | 42.86 | 19.89 | 22.79 |
| $P_2O_5$ | 0.3 | | | 0.25 | 0.22 |
| S | 1.4 | 0.8 | 0.41 | 1.36 | 1.26 |
| $K_2O$ | 1.2 | 0.5 | 1.11 | 1.18 | 1.17 |
| CaO | 72.5 | 0.2 | 6.41 | 67.16 | 60.41 |
| $TiO_2$ | 0.4 | | 2.11 | 0.35 | 0.53 |
| $MnO_2$ | | | 23.95 | | 2.48 |
| $Fe_2O_3$ | 5.7 | 0.9 | 0.31 | 5.3 | 4.75 |
| CuO | 0.1 | | | 0.09 | 0.08 |
| ZnO | 0.1 | | 0.30 | 0/08 | 0.10 |
| SrO | | | 0.05 | | 0.01 |

In addition to Ca(OH)2, another element crucial for concrete strength is $SiO_2$. In HPCfa, the $SiO_2$ content is 3% higher than in HPC (refer to Table 3), resulting in a stronger silica bond. As detailed earlier, the delayed formation of hydration products, such as fly ash balls with a double layer of Ca(OH)2 and the transformation of ettringite, contributes to the overall strength enhancement. This delay, in turn, fortifies the concrete, making it more resistant to premature cracking.

### Delay in Peak Hydration Heat

There are similarities in the form of hydration heat in HPC and HPCfa. Both have one peak, which in HPC occurs at 8 hours and in HPCfa at 11 hours. The hydration heat peak coincides with the shrinkage peak in both HPC and HPCfa (Figures 4a and 4b; Figures 4c and 4d).

All elements of cement play a role in the formation of heat of hydration. The most prominent are tricalcium aluminate ($C_3A$) with 207 cal/g and free lime with 279 cal/g, while dicalcium silicate contributes the least, with 62 cal/g [28]. The $C_3A$ reaction is as follows:

$$C_3A + 6\,H \rightarrow C_3AH_6$$

$$C_3A + 3\,CSH_2 + 26\,H \rightarrow C_6AS_3H_2$$

$$2C_3A + C_6AS_3H_{32} + 4\,H \rightarrow 3C_4ASH_{12}$$

$C_3A$ reacts with water and also reacts with CSH. It means that some $C_3A$ immediately reacts with water, while others wait for the $C_3S$ and $C_2S$ reaction results in the form of CSH. The pozzolanic reaction that occurs in HPCfa also waits for the hydration product from the $C_3S$ and $C_2S$ reactions in the form of CH. It causes the peak of hydration in HPCfa to be delayed.

$C_3A$ contributed the largest chemical shrinkage and heat of hydration on the first day. As long as $C_3A$ is still dominant in determining shrinkage, there is a close relationship between chemical shrinkage and heat of hydration. The hydration reaction of all

components that release heat reaches its peak at 8-12 hours, after which the hydration heat begins to decrease but the hydration reaction continues to occur. This shows that the $C_3A$ reaction decreases, while the $C_3S$, $C_2S$, and $C_4AF$ reactions continue.

### Silica Fume

The effect of silica fume on autogenous shrinkage is not obvious [9], but the addition of 10-20% silica fume to the mixture increases the autogenous shrinkage strain of the concrete specimen [Sánchez]. The amount of silica fume in this concrete is 8% of the amount of cement (Table 2) so its effect on autogenous shrinkage is negligible. In ternary cement mixtures silica fume acts as a nucleation site which results in an accelerated heat release rate and the total heat released is greater than in binary mixed cement pastes, which contributes to an early increase in age compressive strength [28].

### Fly Ash

The fly ash mixture is class F with a CaO content of > 2% (Table 3), so it is considered high calcium fly ash [21]. High calcium class F fly ash releases alkali. The alkali contained in HPC and HPCfa is potassium (K). The amount of Potassium in both HPCs is the same (Table 3). The difference between the two is that in HPC without fly ash, there is no release of potassium while in HPC with fly ash there is a release of potassium. Alkaline release triggers initial hydration [29].

### The Pattern of Autogenous Shrinkage

The autogenous shrinkage model in HPC is different from HPCfa. A real difference occurs in autogenous shrinkage after the peak of shrinkage occurs (Figures 4a, 4b, 4c, and 4d). Thus, there are differences in the relationship between autogenous shrinkage and heat of hydration in HPC.

### Differences in Autogenous Shrinkage Patterns between HPC and HPCfa

After the peak heat of hydration, expansion of HPCfa occurs at a high rate thereby overcoming shrinkage due to the formation of hydration products. This improvement is similar to decreasing hydration heat. This expansion ability is caused by the migration of alkali metal ions to the fly ash surface in HPCfa, resulting in osmotic tension or tension in the capillaries which makes the particles in HPCfa expand. The expansion is also caused by the addition of ettringite due to the release of Potassium. Alkali release contributes to heat generation [4]. This can be seen in Figure 4d where there is an increase in hydration heat at 18-22 hours, but this release also begins to decrease which is followed by a decrease in heat of hydration. In HPC, hydration drops at the 20th hour at

a high rate, while in HPCfa it drops at the 23rd hour at a lower rate.

Starting at the age of 18 hours, large CH crystals began to grow, while several other fly ash grains showed large differences in morphology, namely that there was a coating on the surface. This sheath generally covers the entire surface intact. This occurs slowly and results in a low rate of shrinkage (18-24 hours) and hydration heat increases at a low rate. HPC is not able to expand like HPCfa because the absence of fly ash. It means there is no osmotic stress and potassium release. This slight expansion is not able to follow the rate of decrease in hydration heat, as a result the autogenous shrinkage strain pattern in HPC after the peak of hydration heat does not follow the pattern of reduction in hydration heat. At 18 hours, and penetration of ettringite become deeper. At around 18 hours of age, there is a second peak of shrinkage due to this, and hydration heat.

Consequently, HPC experiences high shrinkage strains from 8-24 hours or 16 hours, whereas in HPCfa, this occurs at 11-16 hours or 5 hours, with a shrinkage value 57% of HPC. This reduction in the duration of hydration product susceptibility to high stress in HPCfa is about 30% of HPC, making it more resistant to premature cracking.

The hydration heat patterns outlined in Equations 1, 2, and 3 reveal a mutual relationship between strain and hydration heat sensitivity. Notably, autogenous shrinkage in full-scale High-Performance Concrete (HPC) specimens mirrors the pattern and magnitude observed in standard laboratory specimen beams, as indicated by Niken, 2019 [30]. It is noteworthy that this study does not delve into the discussion of hydration heat. Consequently, there is a need for additional research to explore the sensitivity of hydration heat to shrinkage on a full scale.

## CONCLUSION

The effect of incorporating 10% fly ash from the total binder reduces the autogenous shrinkage value of high-performance concrete by up to 57%, delays the temperature and peak hydration for 4 hours so that the concrete bond becomes stronger even though the peak heat of hydration does not decrease (36°C), and shortens the duration of peak shrinkage to 30%.

Autogenous shrinkage in HPC shows the same form as hydration heat until the peak of hydration heat, subsequently, it deviates from the hydration heat pattern due to the absence of osmotic stress caused by metal ion migration facilitated by fly ash. This observation provides a more detailed perspective than Kim's findings in 2009 [16].

The relationship between hydration heat and autogenous shrinkage in concrete with replacement 10% cement by fly ash (HPCfa) is very close and can be expressed as:

Hydration heat in 0-10 hours:
$H_{h\,0\text{-}10}$ = 357216 $\varepsilon_t$ + 26.7
Hydration heat in 10.25-11.00 hours:
$H_{h\,10.25\text{-}11}$ = 357216 $\varepsilon_t$ + 22.6
Hydration heat in 11-24 hours:
$H_{h\,11\text{-}24}$ = 357216 $\varepsilon_t$ + 18.5

The average deviation between the equation and the observed results is 2%. Further exploration into the sensitivity of shrinkage strain to changes in hydration heat is warranted, particularly in full-scale concrete beams.

## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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