

# Catalyzing Biomass Concrete as New Renewable Energy Source for Green Building

Y. K. Yong<sup>1</sup>, H. P. Lee<sup>1\*</sup>, Z. S. Gan<sup>1</sup>, K. S. Tan<sup>1</sup>, J. W. Chong<sup>1</sup>, C. X. Lee<sup>1</sup>, S. Hashma<sup>1</sup>, M. J. Hassan<sup>1</sup>, U. A. Latheef<sup>1</sup>, W. P. Low<sup>1</sup>

<sup>1</sup> Department of Civil Engineering, Faculty of Engineering and Quantity Surveying, INTI International University, 71800 Nilai, Negeri Sembilan, MALAYSIA

\*Corresponding Author: [hoongpin.lee@newinti.edu.my](mailto:hoongpin.lee@newinti.edu.my)  
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## Abstract

This paper focuses on Catalyzed Biomass Concrete (CBC) as a sustainable solution for electricity generation with investigate the viability of using palm oil fuel ash (POFA) as a partial replacement for cement and explore the effects of four types of Polyoxometalates (POMs) as catalysts. By utilizing solar-induced biomass and POMs as catalysts, CBC is employed in compressive strength analysis, voltage tests, and engineering tests. Engineering tests and analyses such as thermogravimetry analysis (TGA), and X-ray fluorescence (XRF) are employed to investigate the engineering properties of different CBC samples and support the research findings. Results show that CBC with Phosphomolybdic Acid + Ferric Chloride excels in voltage generation and compressive strength at day 56, while CBC with Phosphotungstic maintains consistent strength, improving notably from day 7 to 56, indicating reliability as a catalyst. In voltage tests, CBC with Phosphotungstic consistently exhibits stability and voltage generation within the specified temperature range. CBC with Ferric Chloride Solution and Silicotungstic Acid's varying mV values suggest effectiveness dependent on POM content, potentially limiting precise electrical characteristics. These findings highlight the potential of CBC as an environmentally friendly alternative for electricity production in the construction industry.

## 1. Introduction

The world is now rallying around the idea of "green" in response to pressing environmental challenges. Rapid urbanization and technological advances have exacerbated environmental issues, including air pollution, soil degradation, global warming, natural resource depletion, unsustainable waste generation, deforestation, climate change, ozone layer depletion, acid rain, and public health concerns. Climate change, in particular, has led to disasters, loss of life, homelessness, and increased poverty, profoundly impacting our daily lives. It is imperative that we address these issues to safeguard the planet. In 2017, fossil fuels accounted for 64.5% of global electricity generation [1]. However, excessive fossil fuel consumption for electricity, transportation, and machinery has caused significant harm to the environment. The combustion of these fuels releases large quantities of carbon dioxide, intensifying climate change. Furthermore, it generates pollutants such as sulfur and nitrogen oxides, which play a role in the creation of acid rain. Moreover, it is projected that all fossil fuel reserves will be depleted by 2060 [2]. The Malaysian government aims to reduce Greenhouse Gas Emissions (GHG) emission intensity by 45% across the economy based on Gross Domestic Product (GDP) by 2030. Additionally, the country aspires to achieve net-zero GHG emissions by 2050 [3]. However, the Environmental Performance Index (EPI) 2022 score

for Malaysia has unfortunately decreased, with ranking 130th, In 2020, Malaysia ranked 68th out of 180 countries, and 75th in 2018. This position is notably lower than that of neighbouring countries, with Thailand at 108th and Singapore at 44th [4], [5].

In the construction industry, the production of concrete using cement poses a significant challenge to the construction industry due to its detrimental impact on the global environment. Cement, which consists mainly of calcium carbonate, releases a substantial amount of carbon dioxide (CO<sub>2</sub>) during decomposition [6]. In fact, the building and construction industry is responsible for approximately 39% of global CO<sub>2</sub> emissions [7], significantly contributing to climate change and environmental degradation. Notably, the strength and durability of concrete can be further enhanced by incorporating lignocellulosic biomass (LCB), such as a combination of fly ash (FA) and palm oil fly ash (POFA), as reinforcement. In recent times, cement may not be entirely replaceable by other cementitious materials such as biomass ash like wheat ash, rice straw ash, and POFA; however, partial substitution remains feasible and effective. Based on the investigation by Maschowski [8], the proportion of biomass ash in concrete increased from 10% to 20% as a substitute for fly ash results in improved workability of the concrete. Nevertheless, according to studies conducted by several researchers, the compressive strength of POFA-blended concrete ranging from 10% to 30% was found to be comparable to that of Ordinary Portland Cement (OPC) concrete [9]-[12].

### 1.1 Lignocellulosic Biomass (LCB)

LCB such as agricultural and forest residues is an abundant renewable feedstock for biofuels production [13]. It encompasses non-edible cellulose at 35-50%, hemicelluloses at 20-35% and lignin at 10-25% [14]. Lignin is an important part of plant cell wall and plays the role of filling and bonding in plant tissues [15]. Lignin able to increase the compressive strength in concrete which can act as water-reducing admixture, set retarder and grinding agent [16]. Meanwhile, lignin is also able to increase the compressive strength in concrete which can act as water-reducing admixture, set retarder and grinding agent. Besides, cellulose and lignin are suitable as natural polymers and have been studied for storage and renewable energy in recent years which is able to act as an efficient, safe and reliable electrochemical energy storage material [17]. LCB is primarily derived from plants and is considered a renewable energy source. It can be processed into liquid biofuels or biogas. Previously, the concept of converting biomass into electricity using fuel cell technology was studied [18], this idea was derived from the study, suggesting the possibility of generating electricity directly from LCB by finding an efficient catalyst for energy storage and electron transfer from the biomass.

### 1.2 Palm Oil Fuel Ash (POFA)

For the proposed biomass - palm oil fuel ash (POFA) was one of the common wastes generated from palm oil mill, palm oil shell and palm oil bunches were burned for electricity generation purpose in Palm Oil Mill and then the residue of the burnt become palm oil fuel ash [19]. Palm oil fuel ash (POFA) is a by-product resulting from the combustion of waste material at palm oil power plants. The disposal of POFA has become a concern, particularly as Malaysia stands among the largest palm oil producers [20]. In 2022, Malaysia contributed to 9.1% and 19.7% of the global production and exports of oils and fats, respectively [21]. POFA exhibits high fineness in pozzolanic properties and has been studied for its potential to partially replace Portland cement in concrete [21]-[24].

### 1.3 Catalysts - Polyoxometalates (POMs)

Polyoxometalates (POMs) is a special class of metal (e.g. VV, MoV, NbV, TaV, MoVI, and WVI) oxide polyanion clusters linked together by shared oxygen atoms exhibit highly variable functional properties [25]. Various energy conversion and storage devices have been developed and subjected to the POM functionalization [26]. POMs are structurally and chemically diverse with reactivities leading to use in catalysis and sustainable energy, electronics, sensors, radionuclide capture and biomedical applications [27]. POMs are good catalyst for generation of electricity from biomass. POMs has a great potential as an electron reservoir. Based on the research, has been found that POMs can be used as a good electron mediator biomass fuel cell that can be directly powered with natural polymeric biomasses, such as starch, for electricity generation [25], [28]-[31].

This paper explores the use of four distinct POM types as a catalyst mixture alongside POFA, serving as a partial cement substitute (20% POFA, 80% cement). With reference to research indicating that substitution levels of 10-30% are optimal [9]-[12], 20% POFA was selected to substitute Ordinary Portland Cement. The POFA concrete samples were designed method of 30 MPa. The samples underwent testing under three temperature conditions (ranging from 0°C to 100°C) to evaluate their voltage values. Two primary experiments, compressive and voltage tests, were conducted, complemented by engineering characteristic tests, including thermogravimetry analysis (TGA), and X-ray fluorescence (XRF) to support the findings.

## 2. Experiment Methods

The proportion of OPC and POFA was the constant variable in this research study, while the manipulated variable was the proportion of polyoxometalates powder-ferric chloride "POM 1", phosphotungstic Acid "POM 2", Silicotungstic Acid "POM 3", and phosphomolybdic "POM 4" POFA at a constant portion 20% was used as a partial cement replacement, with the proportion of coarse and fine aggregates also remaining constant, the design mix were tabulated at [Table 1](#).

**Table 1** Concrete design mix based on experimental requirements

Item	Content per kg/m <sup>3</sup>	Content per cube (g)	Content per cube (g)
		50×50×20 mm (120g) Voltage Test	100×100×100 mm (2400g) Compressive Test
Water	170	8.50	170
Fine Aggregate	796	39.80	796
Coarse Aggregate	1,000	50	1000
<b>Cement Content</b>			
80% Cement	328	16.39	328
20% POFA	82	4.10	82
<b>POM % of cement content</b>			
5%	20.5	1.02	20.5
10%	41	2.05	41
15%	61.5	3.07	61.5
20%	82	4.10	82
25%	102.5	5.12	102.5
30%	123	6.15	123
35%	143.50	7.17	143.50
40%	164	8.20	164

The content for aggregates was kept constant over different concrete cube samples. A total of 30 cubes with the dimension of 100 mm x 100 mm x 100 mm were formed for the compressive test and 50 mm x 50 mm x 20 mm for voltage test. Compressive strength tests were conducted in compliance with ASTM C39/C39M. In the engineering tests, a small portion of the concrete sample was ground and collected for analysis. Subsequently, the prepared samples were placed under the TGA and XRF instruments to generate the data. The purpose of this research study is to find out the optimum varies types of POM content with achieving the objectives of this research study, which are achieving target mean strength, highest electricity generation and identify the characteristics of the materials.

## 3. Results and Analysis

### 3.1 Compressive Test

A total of 30 cubes with the fixed amount of catalyst had undergone compressive strength on 7th day, 28th day and 56th day. The fixed amount of the catalyst chemical being used in the compressive strength were 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% of binder content. The compressive strength of POFA concrete (concrete in which POFA replaces 20% of the cement) and a POFA-catalyst concrete was compared. The outcome for the Compressive test as graphed below.

As shown above, the compressive strength testing reveals intriguing insights into the performance of CBC samples with varying percentages of POM. CBC-POM 1 (see [Fig. 1](#)) shows a notable improvement in strength on day 56, particularly at 5% POM addition, where it achieves a peak compressive strength of 28 MPa. However, as the POM content increases beyond this optimal point, strength gradually declines. This suggests a nuanced relationship between POM concentration and concrete strength, indicating that while a certain amount of POM enhances strength, excessive POM may have diminishing returns or adverse effects on mechanical properties.

In contrast, CBC-POM 2 (see [Fig. 2](#)) demonstrates remarkable consistency in strength across different POM concentrations. Even at higher POM percentages, the concrete maintains its strength, with day 56 results surpassing those of day 7. This suggests that incorporating POM in CBC-POM 2 does not negatively impact its mechanical performance, indicating a robust and stable interaction between POM and the concrete matrix.

However, CBC-POM 3 (see Fig. 3) exhibits more complex behaviour, with its compressive strength showing irregular patterns as the POM content varies. While certain concentrations, such as 5%, 10%, and 25% POM, result in respectable strength values, reaching up to 11.895 MPa on day 56, higher percentages lead to significant decreases in strength. Notably, CBC-POM 3 experiences a complete loss of strength, registering 0 MPa on day 7, when POM content reaches 35% and 40%. This suggests that the influence of POM on concrete strength in CBC-POM 3 is highly dependent on the specific concentration used, with an optimal range for enhancing mechanical properties.

Unfortunately, CBC-POM 4's (see Fig. 4) compressive test results are inconclusive due to issues encountered during the un moulding process. This underscores the importance of considering not only the chemical composition but also the practical aspects of concrete production and handling when incorporating additives like POM.

Overall, the compressive strength data highlights the complex interplay between POM concentration and concrete performance, emphasizing the need for careful optimization and consideration of various factors in developing CBC formulations for enhanced mechanical properties and durability.

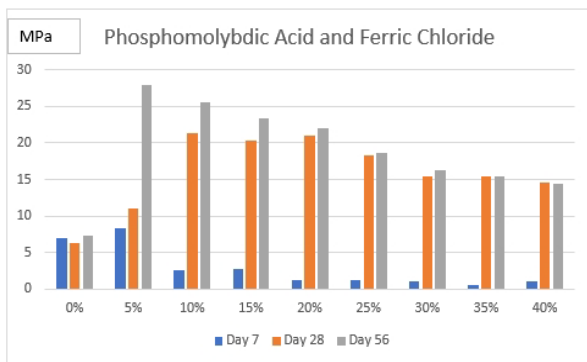


Fig. 1 Compressive result for CBC-POM 1

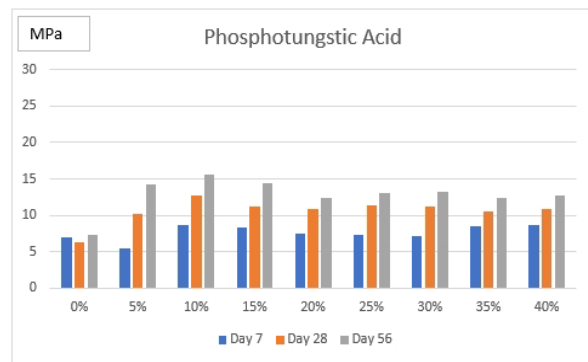


Fig. 2 Compressive result for CBC-POM 2

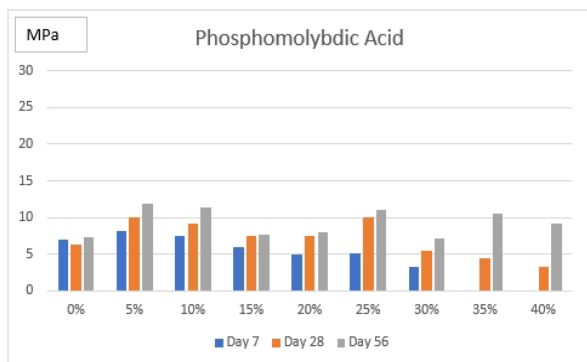


Fig. 3 Compressive result for CBC-POM 3



Fig. 4 Unsuccessful concrete un mould for CBC-POM 4

### 3.2 Voltage Test

In the voltage test, there were 24 specimens casted where each 3 were containing different percentage of catalyst from 5% to 40% with increment of 5%. Voltage test been conducted to investigate the ability of concrete specimen with various percentages of catalyst chemical to generate voltage under various surrounding temperatures. CBC-POM (see Fig. 5) exhibits an overall increasing trend in voltage generation for most catalyst percentages, indicating a potential enhancement in electrical activity with rising temperatures. Notably, the 40% catalyst concentration displays the most stable and optimal performance, consistently showing voltage increases across temperature ranges. This suggests that a higher catalyst percentage may lead to more reliable electrical properties in the concrete mixture, particularly at elevated temperatures. The consistent upward trend in voltage generation with increasing catalyst concentration supports the notion that the 40% concentration provides the most favourable conditions for enhanced electrical activity within the concrete.

CBC-POM 2 (see Fig. 6) also demonstrates increasing voltage trends with rising temperatures, with peaks observed at higher temperature ranges. However, the 25% catalyst concentration appears to yield the most stable performance, showing consistent voltage increases, particularly at elevated temperatures. While other concentrations exhibit fluctuations in voltage generation, the 25% concentration maintains relatively steady

performance across temperature ranges. This suggests that the 25% catalyst concentration may offer a balance between enhanced electrical activity and stability in the concrete mixture.

On the other hand, CBC-POM 3 (see Fig. 7) and CBC-POM 4 (see Fig. 8) both display varied responses in voltage generation across different catalyst percentages and temperature ranges. While certain concentrations show increasing voltage trends with rising temperatures, stability is less consistent compared to CBC-POM 1 and CBC-POM 2. For instance, CBC-POM 3 shows fluctuations in voltage generation across various catalyst percentages, with less clear trends in stability. Similarly, CBC-POM 4 exhibits varied voltage generation responses, with some concentrations displaying relatively stable performance, while others show fluctuations.

In summary, while all CBC-POM variations demonstrate potential for enhancing voltage generation in concrete, CBC-POM 1 with a 40% catalyst concentration offers the most stable and optimal performance across various temperatures. Further investigation is warranted to understand the specific mechanisms driving these observed trends and to optimize the electrical properties of catalysed biomass concrete for various applications.

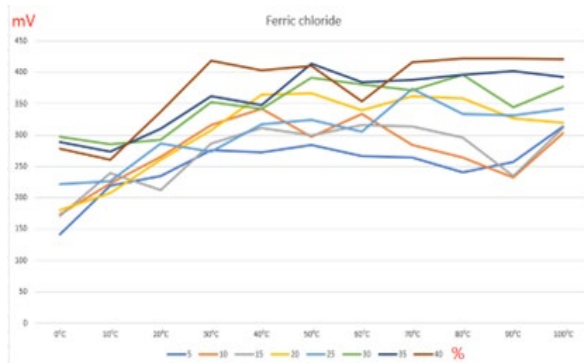


Fig. 5 Voltages Data Chart for CBC-POM 1

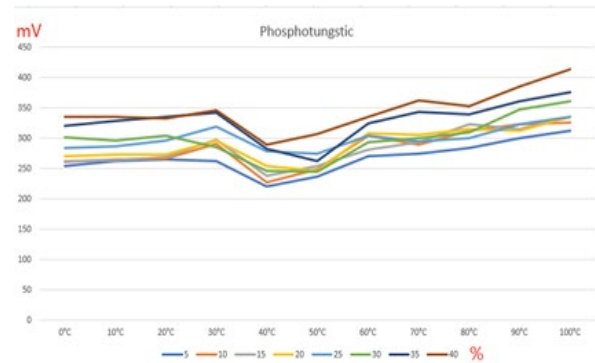


Fig. 6 Voltages Data Chart for CBC-POM 2

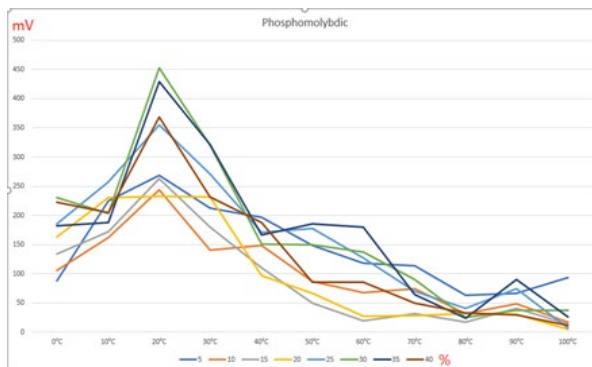


Fig. 7 Voltages Data Chart for CBC-POM 3

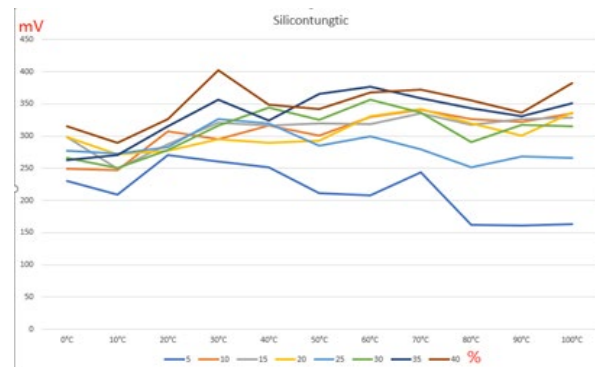


Fig. 8 Voltages Data Chart for CBC-POM 4

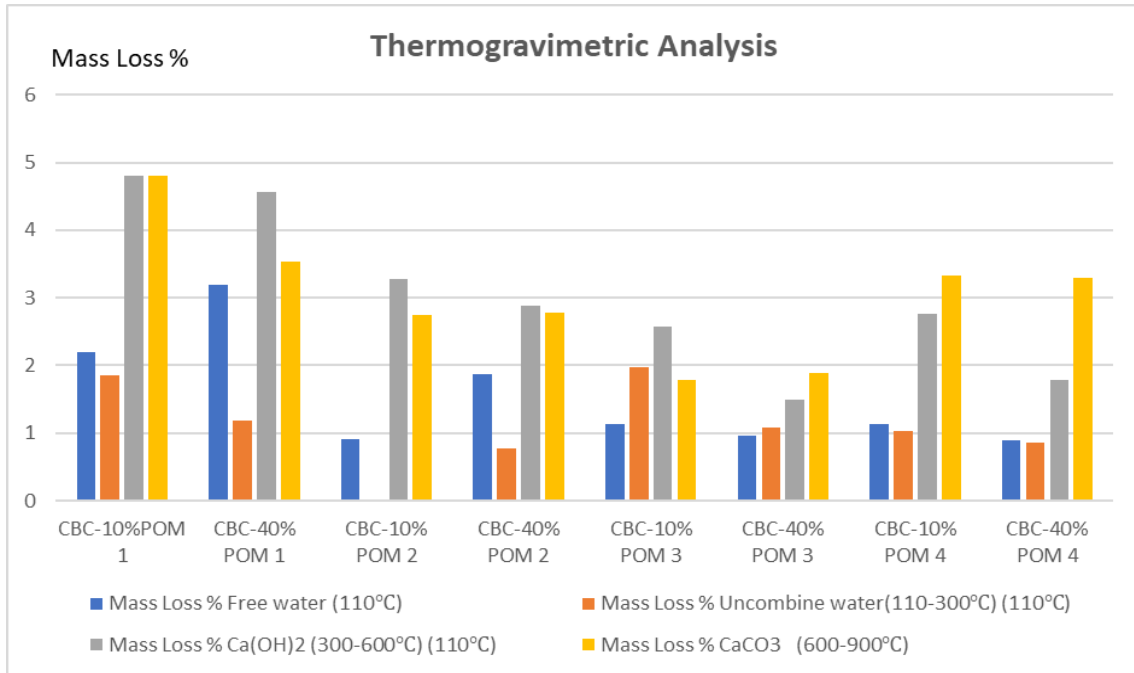
### 3.3 Thermogravimetry Analysis (TGA)

TGA data was analyzed to determine the mass loss as a function of temperature. This can provide insights into the thermal degradation of the sample and the effectiveness of the catalyst in promoting the degradation of the biomass.

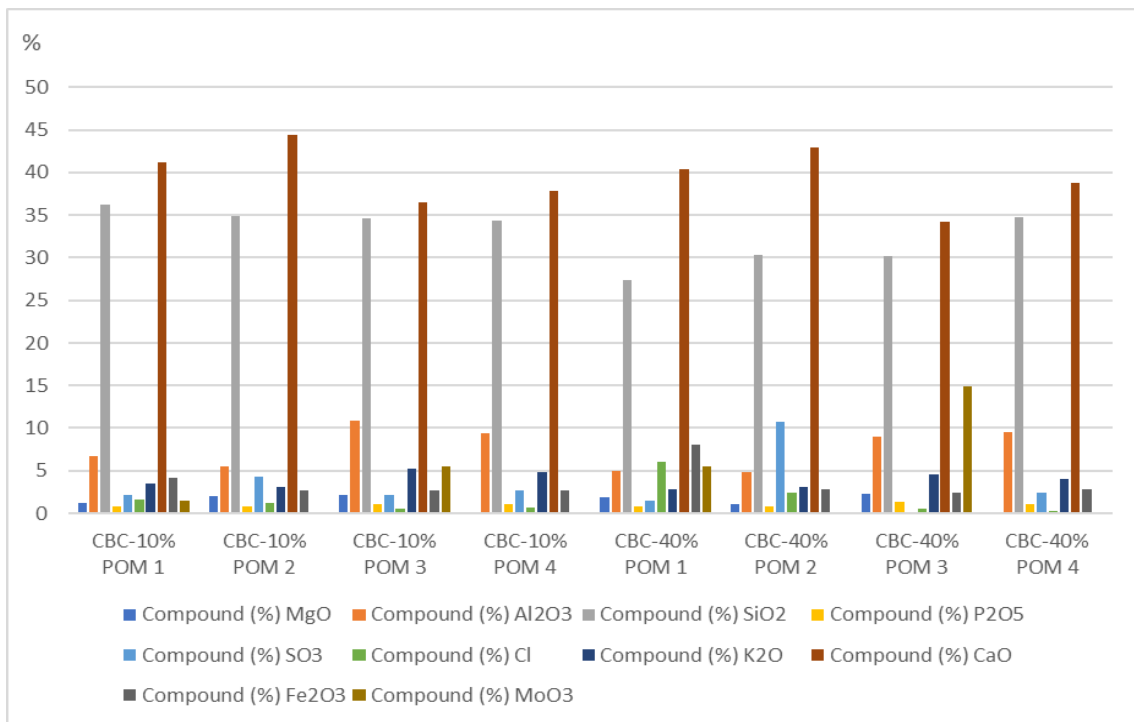
In Fig. 9, the Thermogravimetric Analysis (TGA) data reveals intriguing insights into the thermal behaviour of CBC samples treated with various concentrations of POM. CBC-POM 1 exhibits a notably higher percentage of mass loss in free water, with CBC-40% demonstrating a mass loss of free water at 3.18%. Similarly, samples treated with CBC-40% POM 2 show the second-highest percentage of mass loss in free water, at 1.85%. Remarkably, both these sample groups demonstrate optimal strength in compressive tests compared to others, suggesting an optimal water content crucial for concrete strength. Excessive water content can lead to increased porosity and a less dense structure. Additionally, accelerated water loss in samples with high initial water content may indicate favourable curing conditions, enhancing hydration.

Furthermore, both CBC-POM 1 and CBC-POM 3 exhibit a significant range of percentage mass loss in uncombined water, possibly attributed to the presence of Phosphomolybdic Acid. Moreover, CBC-POM 1 displays substantial mass loss in  $\text{Ca}(\text{OH})_2$  and  $\text{CaCO}_3$ . This phenomenon serves as a valuable indicator of concrete hydration progress, strength development, carbonation susceptibility, and durability. Monitoring  $\text{Ca}(\text{OH})_2$  content can correlate with concrete strength development, while  $\text{CaCO}_3$  mass loss provides insights into concrete durability,

with higher losses indicating increased vulnerability to environmental factors like carbon dioxide exposure. These findings underscore the importance of TGA analysis in guiding concrete mix designs and maintenance strategies for enhanced performance and longevity.



**Fig 9** Thermogravimetric analysis based on different portion POM in CBC



**Fig 10** XRF (X-ray fluorescent) data with different POM

### 3.4 X-Ray Fluorescence (XRF)

It's a non-destructive analytical technique used to determine the elemental composition of materials. XRF analyzers determine the chemistry of a sample by measuring the fluorescent (or secondary) X-ray emitted from a sample when it is excited by a primary X-ray source. Each of the elements present in a sample produces a set of

characteristic fluorescent X-rays (“a fingerprint”) that is unique for that specific element, which is why XRF spectroscopy is an excellent technology for qualitative and quantitative analysis of material composition [32].

In the X-ray Fluorescence (XRF) data shown in Fig. 10, SiO<sub>2</sub> and CaO emerge as the predominant elements within the samples, playing crucial roles in concrete properties. SiO<sub>2</sub>, abundant in all samples but most notably in CBC-10% POM 1 with 36.210% SiO<sub>2</sub> content, enhances concrete strength by fostering additional C-S-H gel through a pozzolanic reaction with calcium hydroxide. This reaction improves durability by reducing permeability and fortifying the concrete against water ingress, chemicals, and harmful substances, thus enhancing resistance to freeze-thaw cycles and chemical attacks. Conversely, CBC-40% POM 1 exhibits the lowest SiO<sub>2</sub> content at 27.379%. Despite the seemingly significant disparity, the difference in SiO<sub>2</sub> content remains relatively small across samples.

Furthermore, both CBC-POM 1 and CBC-POM 2 demonstrate significantly higher percentages of CaO content compared to others, with CBC-POM 1 registering 40.398% and 41.227% for CBC-10% POM 1 and CBC-49% POM 1, respectively, and CBC-POM 2 recording 44.443% for 10% POM 2 and 42.951% for 40% POM 2. This elevated CaO content contributes to better compressive strength performance in both sample groups, attributed to the optimal duration of setting facilitated by CaO during the curing stage of CBC.

However, attention must be paid to the compound SO<sub>3</sub>, also found in CBC samples, as it can influence concrete strength. While small amounts of SO<sub>3</sub> can expedite early strength gain, exceeding 5% may lead to performance deterioration and structure destruction. Additionally, excessive SO<sub>3</sub> concentrations, as observed in CBC-40% POM 2 with 10.712%, can act as a retarder, prolonging the setting time of cement. Other POM variants exhibit SO<sub>3</sub> content ranging from 0% to 2.680%, suggesting the need to carefully consider SO<sub>3</sub> levels and curing methods for optimal concrete performance.

#### 4. Conclusion

In conclusion, the optimization of catalysts for biomass concrete involves a complex interplay of factors, including compressive strength, electrical conductivity, mass loss characteristics, and chemical composition. Based on the comprehensive analysis conducted in this study, it is evident that CBC-POM 1 and CBC-POM 2 stand out as promising catalyst options.

CBC-POM 2 consistently maintained its strength and demonstrated stable electrical characteristics within the specified temperature range. This makes it a reliable choice for applications requiring both structural integrity and electrical performance. Additionally, CBC-POM 1 showed excellent initial strength when a moderate amount of POM was added, although its strength diminished with higher POM content.

The TGA results indicated that the mass loss in free water and uncombined water varied among the CBC-POM samples. CBC-POM 1 and CBC-POM 2 showed optimal strength in compressive tests, likely due to their optimal water content. Furthermore, CBC-POM 1 and CBC-POM 3 exhibited a high percentage mass loss in uncombined water, potentially influenced by the presence of Phosphomolybdic Acid. The mass loss of Ca(OH)<sub>2</sub> and CaCO<sub>3</sub> in biomass concrete serves as important indicators of the concrete's hydration progress, strength development, and durability.

XRF analysis revealed that SiO<sub>2</sub> and CaO were the major elements in the samples. Higher SiO<sub>2</sub> content enhances concrete strength and durability, while higher CaO content accelerates early strength development. Careful consideration of these elements is essential in optimizing concrete properties, as excessive CaO can lead to challenges during curing.

In summary, the comprehensive examination of CBC samples incorporating varying percentages of POM reveals valuable insights into their mechanical, electrical, thermal, and elemental characteristics. The compressive strength testing highlights the nuanced relationship between POM concentration and concrete strength, with CBC-POM 1 exhibiting significant enhancement in strength at 5% POM addition, while CBC-POM 2 demonstrates consistent strength across different concentrations. However, CBC-POM 3 displays irregular strength patterns, emphasizing the critical role of optimal POM concentration. Practical challenges encountered with CBC-POM 4 underscore the importance of considering practical aspects in concrete production.

The analysis of energy conversion and storage systems underscores the potential of POMs, particularly phosphomolybdic acid, as efficient electron mediators and proton carriers in power generation. Based on studies, phosphomolybdic acid's ability to facilitate electron extraction from biomass during oxidative depolymerization processes makes it a promising catalyst for electricity generation from natural biomasses [18], [33]. Additionally, the effectiveness of ferric chloride as an electron transfer mediator further supports the potential of POM-functionalized CBC systems for efficient energy conversion [34]-[36].

Overall, the findings suggest that the optimal design incorporating POM 1 (ferric chloride + phosphomolybdic acid) offers promising prospects for enhancing concrete properties and facilitating energy conversion processes. Further research and optimization efforts are warranted to fully harness the potential of POM additives in CBC formulations for sustainable infrastructure development and energy applications.

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## Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** H. P. Lee, Y. K. Yong ; **data collection:** Y. K. Yong, H. P. Lee; **analysis and interpretation of results:** Y. K. Yong, H. P. Lee, Z. S. Gan, K. S. Tan, J. W. Chong, C. X. Lee, S. Hashma, M. J. Hassan, U. A. Latheef, W. P. Low; **draft manuscript preparation:** Y. K. Yong. All authors reviewed the results and approved the final version of the manuscript.*

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