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Mechanical Properties of Self-Compacting Concrete Incorporating Palm Oil Fuel Ash (POFA) and Gypsum Powder as Partial Cement Replacement

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Abstract

This study investigates sustainable substitutions to Ordinary Portland Cement (OPC) in Malaysia's construction sector, aiming on the environmental impact instigated by greenhouse gas emissions. The research explores using 20% palm oil fuel ash (POFA) and 5% to 15% gypsum powder (GP) as partial cement replacements in self-compacting concrete (SCC). The study utilized cement, sand, coarse aggregate, POFA, and GP. POFA was sourced from a palm oil plant, processed into fine powder, and combined with gypsum powder as a partial cement replacement. The SCC mixtures followed a specific ratio of 1:2:1.7 for cement, sand, and coarse aggregate, with varying percentages of POFA and GP. The objective was to achieve a compressive strength of 30 MPa with SCC densities between 2000–2600 kg/m^3. Concrete cubes (100 mm x 100 mm x 100 mm) were cast for compressive strength testing, and cylinders (100 mm x 200 mm) were used to measure the modulus of elasticity and Poisson’s ratio. The samples were cured in water for 7 and 28 days. The specimens were subjected to compressive strength tests using standardized testing machines. Cylinders were tested to measure the deformation under load, following guidelines to assess stiffness and elastic properties. The significance of this research lies in its contribution to sustainable construction by offering alternative materials to OPC towards reduce carbon emissions. By incorporating waste materials such as POFA and GP, the study not only addresses environmental concerns however also suggests practical solutions to decrease cement demand. This approach can help reduce the environmental footprint of the construction industry and encourage the recycling of agricultural by-products. This paper advances the understanding of how waste materials can be integrated into concrete production, proposing a viable alternative to traditional methods with significant environmental and industrial benefits.

1. Introduction

Concrete is the most widely used construction material globally due to its strength, durability, and versatility. However, the production of Ordinary Portland Cement (OPC), a critical component of concrete, has been identified as a major contributor to greenhouse gas emissions, accounting for about 7-8% of global CO2 emissions. As environmental concerns escalate, researchers are seeking alternative materials that can partially or fully replace cement to reduce the carbon footprint of the construction industry [1].

One promising approach is the use of supplementary cementitious materials (SCMs) derived from industrial by-products or natural resources. Palm oil fuel ash (POFA), a by-product of the palm oil industry, and gypsum powder (GP), a natural mineral, have gained attention as viable SCMs. POFA, abundant in palm oil-producing countries like Malaysia, is rich in silica and possesses pozzolanic properties, making it a suitable material for partial cement replacement [2]. Similarly, gypsum powder, commonly used in construction for drywall and plaster, can enhance the setting and mechanical properties of concrete when used in the right proportions [3].

Self-compacting concrete (SCC) is another innovation that is gaining popularity due to its ability to flow under its own weight and fill formwork without the need for mechanical vibration. This unique property of SCC makes it highly suitable for use in areas with high reinforcement concentrations or complex forms, reducing labour costs and increasing construction efficiency [4]. The combination of SCC with sustainable materials like POFA and GP presents an opportunity to create eco-friendly, high-performance concrete for the construction industry.

Over the past few decades, research has explored various SCMs to reduce the reliance on OPC. Fly ash, ground granulated blast furnace slag (GGBS), and silica fume have been extensively studied for their ability to improve the mechanical properties and durability of concrete [5]. Similarly, POFA has been investigated as a partial cement replacement in various forms of concrete, demonstrating its potential to enhance the long-term strength and sulphate resistance of high-performance concrete [6]. POFA's pozzolanic activity, derived from the high silica content, contributes to the formation of calcium silicate hydrate (C-S-H), the key binding agent in cementitious systems. Additionally, gypsum powder has been shown to regulate the setting time of cement and improve compressive strength when used in small percentages [7].

Despite these advancements, the combined use of POFA and GP in self-compacting concrete (SCC) remains underexplored. Most studies have focused on either POFA or GP in isolation, and little attention has been given to the synergistic effects of these materials when used together. This research aims to fill that gap by examining the mechanical properties of SCC, incorporating both POFA and GP as partial replacements for OPC. The integration of these materials could potentially reduce cement consumption, enhance concrete performance, and contribute to more sustainable construction practices.

The primary research problem addressed in this study is the environmental impact of cement production and the need for sustainable alternatives in the construction industry. While various SCMs have been proposed, the potential of combining POFA and GP in SCC has not been thoroughly investigated, particularly in optimizing mechanical properties such as compressive strength, modulus of elasticity, and Poisson's ratio.
The aims of this research are:
(i) To evaluate the mechanical properties of self-compacting concrete incorporating 20% palm oil fuel ash (POFA) and varying percentages (5-15%) of gypsum powder (GP) as partial cement replacements.
(ii) To determine the optimal mix proportions that balance early strength and long-term performance, offering a sustainable and high-performance alternative to traditional concrete mixes.
(iii) To provide a comprehensive assessment of the effects of POFA and GP on the compressive strength, modulus of elasticity, and Poisson's ratio of SCC, contributing to the development of eco-friendly construction materials.

2. Material

2.1 Self -Compacting Concrete (SCC)

SCC, developed in 1988 by Professor Hajime Okamura, offers superior fluidity, workability, and strength compared to traditional concrete [8]. Unlike conventional concrete, SCC flows effortlessly through restricted spaces without segregation or bleeding. It brings commercial advantages by enabling easy placement in complex forms with dense reinforcement, achieved using affordable pozzolan materials to reduce cement content [9]. SCC eliminates the need for vibration during compaction, as its unique properties allow for uniform compaction through the force of gravity [10].

2.2 Superplasticizer

The main difference between SCC and regular concrete lies in the extensive use of Poly Carboxylic Ether (PCE) superplasticizers, crucial for achieving self-compacting properties and a low yield stress. These superplasticizers, typically with a PCE backbone, enhance flowability and workability by absorbing onto cement and mineral particles' surfaces [11]. Regardless of their type, they generally possess a negatively charged backbone, facilitating attraction to positively charged surfaces during the concrete mixture flow [12]. This absorption occurs mainly on the surfaces of C3A and C4AF in the cementitious system and, additionally, on mono-sulphate and ettringite, with ettringite showing the highest zeta potential [13].

2.3 Material of SCC

2.3.1 Ordinary Portland Cement

The cement industry, crucial for economic growth, emits 2.2 Gt of CO2 annually, contributing 7-8% of global greenhouse gas emissions [1]. Fly Ash, a coal-burning byproduct, proves a potential cement substitute, enhancing compressive strength in Ultra-High-Performance Concrete (UHPC) [14]. Another study explores POFA and eggshell powder (ESP) in SCC, showing advantages in concrete production [15]. Pulverized Fuel Ash (PFA) as a cement substitute in geopolymer concrete exhibits promise but has an optimal replacement threshold [16]. Research on materials like Ground Granulated Blast-furnace Slag (GGBS), Silica fume, and fine limestone aims to identify optimal proportions for sustainable concrete in the construction industry [16].

2.3.2 Aggregate

Aggregates play a vital role in enhancing concrete density, reducing the reliance on cement and water, and contributing to overall strength. They form approximately 75% of concrete volume and impact both fresh and hardened concrete properties. Despite being commonly seen as inert particles, aggregates possess physical, thermal, and occasional chemical characteristics that influence concrete performance [5].

2.3.3 Fine Aggregate

The fine aggregate in this study adhered to ASTM C33 grading requirements (Table 1) and was prepared by drying at room temperature for 24 hours to attain the Saturated Surface Dry (SSD) condition [17]. Sieving was conducted to limit the maximum particle size to 4.75mm, ensuring consistency and suitability. Fig. 1 displays the fine aggregate utilized in project.

Fig. 1 *Fine aggregate*

Table 1 *Grade for aggregate*

Progressing for Small Aggregates (ASTM C33)	
Sieve No.	**Percentage of Sieve Passing**
3/8 in.	100
No. 4	95-100
No. 8	80-100
No. 16	50-85
No. 30	25-60
No. 50	10-30
No. 100	2-10

2.3.4 Coarse Aggregate

To meet specifications, the coarse aggregate was sieved to confirm a maximum particle size not exceeding 12mm (see Fig. 2). Employing 12mm aggregates aimed to reduce voids in the concrete mix, enhancing overall strength. The selection of larger-sized aggregates also contributed to improving concrete quality by avoiding low-strength aggregates in the specimens.

Fig. 2 *Coarse aggregate*

2.3.5 Water

Water is vital in cement hydration, but more than is needed is often added for desired fluidity, resulting in three water types in cement paste: chemically reacted, absorbed, and free water. Chemically reacted water forms hydration products, challenging to remove. Absorbed water affects shrinkage and creep behaviour, while free water, existing outside the C–S–H gel, influences capillary pores during evaporation. Knowledge of these water types is crucial for understanding concrete behaviour [18].

2.4 Supplementary Cementitious Materials

2.4.1 Palm Oil Fuel Ash

In Malaysia's palm oil industry, the success story is marred by a significant environmental challenge – the generation of Palm Oil Fuel Ash (POFA) as solid waste. Despite its environmental impact, approximately 5% of POFA can be repurposed as a pozzolanic material in the concrete industry. The ash, produced from burning palm shells and fibres in biomass thermal power plants at temperatures of 800 to 1000 °C, holds the potential for beneficial use [19]. POFA, a Class C pozzolan, reacts with cement paste, forming C-S-H and enhancing sulphate resistance. Finer particles and higher replacement rates improve compressive strength over time. In High-Performance Concrete, 10 µm-sized POFA achieves high strength (60 MPa to 86 MPa) with reduced expansion. Chemical analysis confirms its pozzolanic suitability, with increasing unburned carbon resulting in a darker colour [20].

The POFA for this study was collected from the Ban Dung Palm Oil Industries Sdn Bhd processing plant in Batu Pahat Johor, as shown in Fig. 3(a). POFA was processed by sieving and drying [21]. Then ground to a fine powder using a Los Angeles Abrasion machine, it was then sieved to a 75 µm size, similar to cement particles. Retaining moisture, POFA was prepared at Advanced Material Laboratory (E17) for use in this study, serving as a 20% partial cement substitute based on its optimal ratio in previous research [22]. Fig. 3(b) displays the processed POFA. Table 2 provides Standard Sieve Size specifications per the 2007 American Concrete Institute (ACI) guidelines [17], serving as a reference for concrete materials analysis and characterization.

(a) (b)

Fig. 3 *(a) Collection of POFA; (b) Processed POFA*

Table 2 *Standard sieve size*

Standard sieve size (µm)	Alternative	Nominal Sieve Opening (mm)
300	No. 50	0.300
150	No. 100	0.150
75	No. 200	0.075

2.4.2 Gypsum Powder

Gypsum powder, derived from white mineral rock, offers advantages like lightweight, fire resistance, and ease of shaping. Composed of Calcium, Sulphur, Oxygen, and Hydrogen, it is a cost-effective construction material with lower energy consumption (4–5 times less heat energy) than Portland cement, reducing allergy risks [23]. GP, or calcium sulphate dihydrate, is a versatile material widely used in construction for making drywall, plaster, and cement. With inherent fire resistance and excellent sound insulation properties, it offers easy mixing with water for quick and convenient installation [3].

Studies have explored gypsum powder as a partial cement substitute in concrete mixes due to its pozzolanic properties. Research aims to determine the optimal gypsum percentage for enhancing or maintaining concrete properties, focusing on factors like compressive strength and durability. Hydration characteristics and interactions with other cementitious materials are essential aspects studied for a comprehensive understanding of performance [7].

In this research, GP is utilized as a crucial component. This finely ground and powdered form of calcium sulphate, known as gypsum, holds significant importance in fulfilling the objectives of the study. To obtain this essential material, it was sourced from a reputable and established hardware store shown in Fig. 4. The decision to acquire gypsum powder from a hardware store was made to ensure the utmost quality and purity, aligning with the stringent requirements of the research methodology.

Fig. 4 *Gypsum powder*

2.4.3 Superplasticizer (SP)

SP, a water-reducing and set-accelerating agent, was chosen in this research to enhance concrete properties like high early strength, lower water-cement ratio, accelerated set, increased strength, reduced shrinkage, and improved workability. The SP used to enhance flowability in SCC, crucial for effectively filling congested and reinforced structural elements. Their effectiveness depends on factors such as cement composition, ambient temperature, and specific mix design, influencing their impact on SCC performance.

3. Specimen Preparation

3.1.1 Concrete Mix Design

The laboratory trial mix design adheres to [24] guidelines for self-compacting concrete (SCC), targeting a compressive strength within the optimal range of 30 MPa. The initial trial mix used a ratio of 1:2:1.7, aligning with EFNARC standards (see Table 3) that specify an acceptable SCC density range of 2000-2600 kg/m^3. For this trial, a target density of 2300 kg/m^3 was aimed for as the ideal average value.

Table 3 *Standard range of SCC mix composition [24]*

Constituents	Typical Range by Mass (kg/m^3)	Typical Range by Volume (litres/ m^3)
Powder	380-600	
Paste	-	300-380
Water	150-210	150-210
Coarse aggregate	750-1000	270-360
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48-55% of total aggregate weight.	
Water/ Powder ratio by Vol		0.85-1.10
Superplasticizer	0.3%-2.5%	-

3.1.2 Mix Proportions

Table 4 presents the composition of the mix that was utilized throughout this study, specifying the amounts of cement, sand, aggregate, and water content. On the other hand, Table 5 outlines the mix proportions of POFA and GP as substitutes for cement in SCC. These proportions were designed in accordance with the [24] European Guidelines for SCC.

Table 4 *Ratio of material*

Material	Ratio
Cement : Sand : Coarse aggregate	1 : 2 : 1.7
Water/ binder ratio	0.4
Superplasticizer dosage	2% of cement weight

Table 5 *Percentage mix proportion of POFA and ESP to replace cement in SCC.*

Mix Name	% of POFA	% of Gypsum Powder	% of Cement
Control	0%	0%	100%
SSC 20P 0G	20%	0%	80%
SSC 20P 5G	20%	5%	75%
SSC 20P 10G	20%	10%	70%
SSC 20P 15G	20%	15%	65%

3.1.3 Specimen Size and Amount

In the concrete mixing process employed in this study, a meticulously crafted design mix was adhered to, featuring precise proportions for the key components. The design mix utilized a specific ratio of 1:2:1.7 for cement, fine aggregate, and coarse aggregate, respectively. Additionally, a crucial factor in concrete formulation, the water-to-cement ratio, was carefully set at 0.4 to optimize the mixture's properties. The determination of the requisite quantities for cement, sand, and water was an integral step in ensuring the accuracy and consistency of the concrete mix. This involved meticulous calculations to establish the appropriate amounts of each component. Table 6 provides a comprehensive breakdown of the mix proportions for cement, sand, and water, offering a clear representation of the precise quantities employed in the concrete mixture.

Table 6 *Mix proportions for each material*

Mix Name	Cement (kg/m^3)	POFA (kg/m^3)	GP (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
Control	451	0	0	902	767	180	9.02
SSC 20P 0G	361	90.19	0	902	767	180	9.02
SSC 20P 5G	338	90.19	22.54	902	767	180	9.02
SSC 20P 10G	316	90.19	45.1	902	767	180	9.02
SSC 20P 15G	293	90.19	67.65	902	767	180	9.02

3.1.4 Cube and Cylinder Preparation

Sample preparation was carried out using 100 x 100 x 100 mm cube moulds designated for compressive strength test [25]. A total of 30 cubes were utilized, with six cubes assigned for each 7th and 28th day sampling. Meanwhile, the dimensions of the mould utilized in creating the cylinder are 100 x 200 mm. The cylinders were employed to determine the modulus of elasticity. Each sample consisted of three cylinders, making a total of 15 specimens. After a minimum of 24 hours, the cubes and cylinder were de-moulded, enabling the concrete to adequately cure.

3.1.5 Curing

For this study, both cubes and cylinders were stored in a sealed laboratory container and subjected to water curing until reaching maturity. All samples, including the concrete cubes up to the 7th and 28th day and the cylinder specimens up to the 28th day, underwent curing to achieve necessary concrete ageing. Fig. 5 shows the water curing tank.

Fig. 5 *Curing tank*

4. Laboratory Testing

4.1.1 Compressive Strength Test

The aim of this test was to evaluate the compressive strength of concrete using 100mm x 100mm x 100mm cubes. The SCC mix was poured into moulds, and samples were extracted after 24 hours of drying and curing. A total of 30 samples were prepared and tested on the 7th and 28th days following BS EN 12390-3:2009 guidelines. Fig. 6 shows the compressive testing machine.

Fig. 6 *Compressive strength test machine*

4.1.2 Modulus of Elasticity and Poisson's Ratio Tests

The experiment aimed to determine the modulus of elasticity and Poisson's ratio of a cylindrical concrete specimen in megapascal (MPa) units, following standard guidelines. The modulus of elasticity was crucial for establishing the working stress range, which is used in sizing structural members and determining reinforcement quality based on observed strains. Notably, the obtained modulus of elasticity values tended to be lower than those derived from rapid load application. The test was conducted using a universal testing machine (UTM), as depicted in Fig. 7.

Fig. 7 *Universal testing machine (UTM)*

5. Results and Discussion

5.1 Compressive Strength

The compressive strength test was carried out following the guidelines of BS EN 12390-3:2009 on 30 cubic samples measuring 100 x 100 x 100 mm. These samples underwent water curing for periods of 7 and 28 days [26]. Table 7 presents the average compressive strengths for different mixes, featuring varying percentages of POFA and GP.

The control sample exhibits 21.54 MPa at 7 days and 22.57 MPa at 28 days. SCC 20P 0P (20% POFA) shows notable improvement, reaching 30.45 MPa at 7 days and 34.19 MPa at 28 days, with a 41.36% increase at 7 days and 51.48% at 28 days. SCC 20P 5G has a slight early reduction (-9.56% at 7 days) but improves by 6.91% at 28 days, indicating a potential retarding effect of 5% GP. SCC 20P 10G experiences a significant decrease in strength, -49.16% at 7 days and -41.56% at 28 days, possibly due to the adverse impact of 10% GP on hydration. In SCC 20P 15G, strength further decreases (-62.89% at 7 days, -55.07% at 28 days), suggesting 15% GP hinders hydration.

Table 7 *Result compressive strength test of SCC*

Mix Proportion	Average Compressive Strength (MPa)		Difference in Strength Comparison to Control Sample (%)	
	7 days	28 days	7 days	28 days
Control	21.54	22.57	0	0
SCC 20P 0G	30.45	34.19	41.36	51.48
SCC 20P 5G	19.48	24.13	9.56	6.91
SCC 20P 10G	10.95	13.19	49.16	41.56
SCC 20P 15G	8.00	10.14	62.89	55.07

The chart in Fig. 8 visually confirms trends in compressive strength. SCC 20P 0G excels, emphasizing the positive impact of 20% POFA without GP. Increasing GP content adversely affects strength, with SCC 20P 10G and SCC 20P 15G exhibiting the lowest strengths.

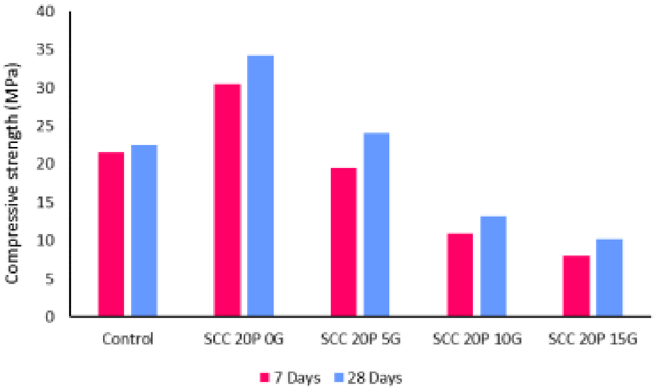


Fig. 8 *Average compressive strength of SCC*

Fig. 8 underscores the need to balance POFA and GP for optimal compressive strength, affirming the benefits of 20% POFA. The strength reduction is attributed to gypsum accelerating cement setting times.

In summary, POFA positively influences strength, especially at later ages. Moderate GP (5%) benefits long-term strength, but caution is advised with higher proportions (10% and 15%). Further research is recommended. Fig. 8 visually confirms trends, highlighting the superiority of SCC 20P 0G and the negative impact of increased GP on compressive strength.

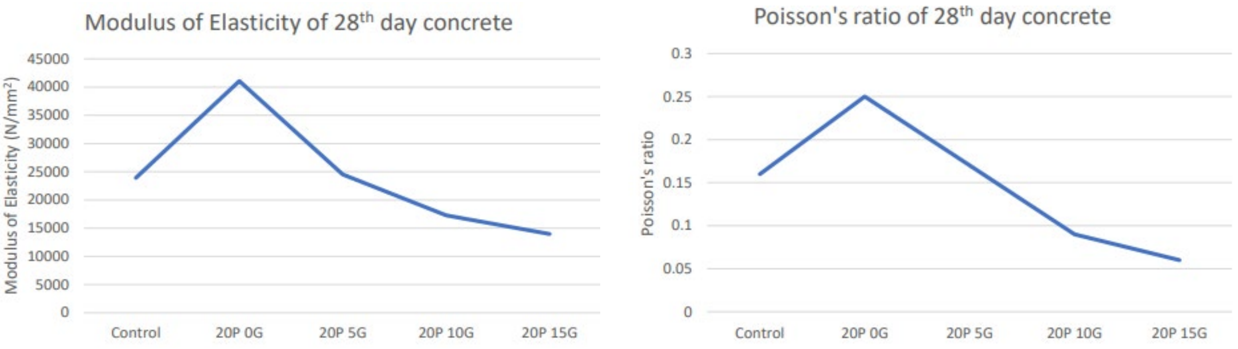
5.2 Modulus of Elasticity and Poisson's Ratio

The Modulus of Elasticity (MOE) assesses a material's resistance to deformation under vertical loading on a 100mm diameter, 200mm length cylindrical sample [27]. Compression loads were applied, and strain gauges measured deformation, with results derived from the stress-strain graph. Table 8 below shows the outcomes of MOE and Poisson's ratio testing averages for all specimens.

Table 8 *Results average of modulus of elasticity and Poisson's ratio*

Specimen	Average Modulus of Elasticity (N/mm²)	Poisson's Ratio
Control	23919	0.16
20P 0G	41065	0.25
20P 5G	24527	0.17
20P 10G	17272	0.09
20P 15G	13962	0.06

The Modulus of Elasticity (MOE) of SCC decreases significantly with increasing GP dosage. The control sample has an MOE of 23919 N/mm^2 and a Poisson's ratio of 0.16. In 20P0G, with 20% POFA, the MOE substantially increases to 41065 N/mm^2, indicating enhanced stiffness. However, in mixes with GP (20P5G, 20P10G, and 20P15G), the MOE progressively decreases, reaching 13962 N/mm^2 in 20P15G. This decline suggests compromised elastic properties, with 15% GP leading to the most significant reduction. Poisson's ratio trends align with these observations. Fig. 9 visually represents these trends.



(a) (b)

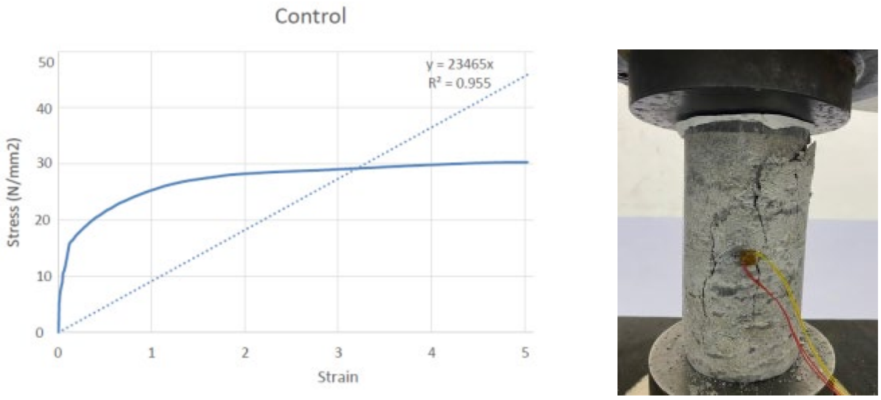
Fig. 9 *(a) MOE values of SCC for 28th day; and (b) Poisson's ratio*

5.3 Stress and Strain Relationship

The stress-strain curve visually illustrates concrete's response to compressive forces, depicting changes in compressive strain during loading. As the load increases, stress rises, and micro-cracks develop, influencing specimen deformation.

5.3.1 Control Specimen

In Fig. 10(a), the blue curve depicts the stress-strain relationship, with the initial steep segment representing elastic deformation. The dotted line (equation: "y = 23465x") in this phase calculates the modulus of elasticity, supported by a strong linear relationship (R^2 = 0.955). As strain increases, the curve plateaus, marking the onset of plastic deformation. In this phase, microcracks emerge, culminating in failure, as illustrated in Fig. 10(b).



(a) (b)

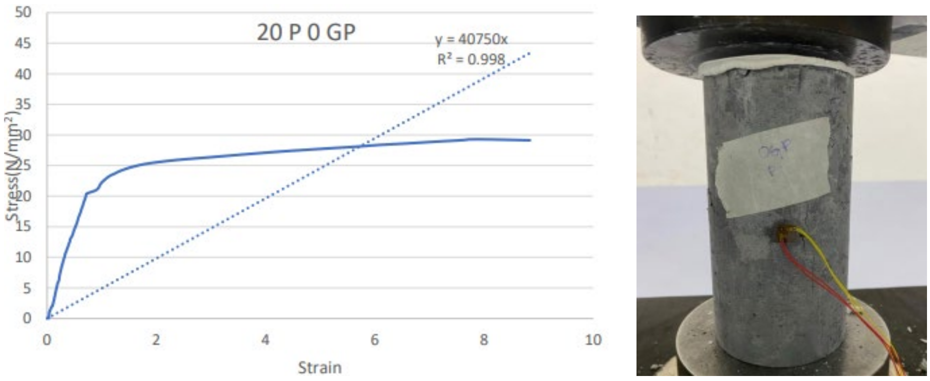
Fig. 10 *(a) Stress vs strain control; and (b) Control failure crack*

5.3.2 20P0GP Specimen

In Fig. 11(a), the initial linear segment signifies the elastic region, halting at 20 N/mm^2. The yield point at 23 N/mm^2 denotes the stress where elastic deformation transitions to plastic deformation. The highest recorded data was 29.3 N/mm^2 stress and 8.8 strain, showcasing linear stress increase leading to eventual failure, as seen in Fig. 11(b). The sample's return to its original shape after load removal indicates elastic behaviour.

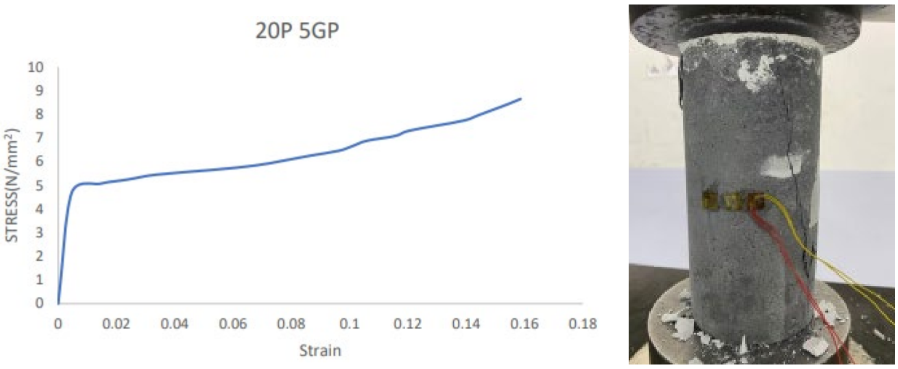
5.3.3 20P5GP Specimen

In Fig. 12(a), the initial linear segment, ceasing at 4.9 N/mm^2, signifies the elastic region. Due to concrete's brittleness, a distinct yield point is often absent. The highest recorded data was 8.65 N/mm^2 stress, and the sample exhibited sudden failure, as depicted in Fig. 12(b), with linear stress increase leading to failure.



(a) **(b)**

Fig. 11 *(a) Stress vs strain 20P0GP; and (b) 20P0GP failure crack*

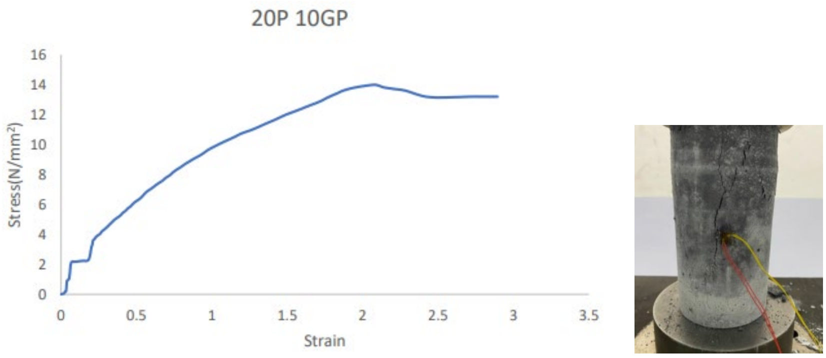


(a) **(b)**

Fig. 12 *(a) Stress vs strain 20P5GP; and (b) 20P5GP failure crack*

5.3.4 20P10GP Specimen

In Fig. 13(a), this sample lacks a distinct elastic region, suggesting non-elastic behaviour in the conventional sense. The absence of a clear elastic region, as shown in Fig.13(b), indicates that the sample does not return to its original shape after the applied load is removed. This lack of elasticity may be attributed to stress concentration and early-stage crack initiation.

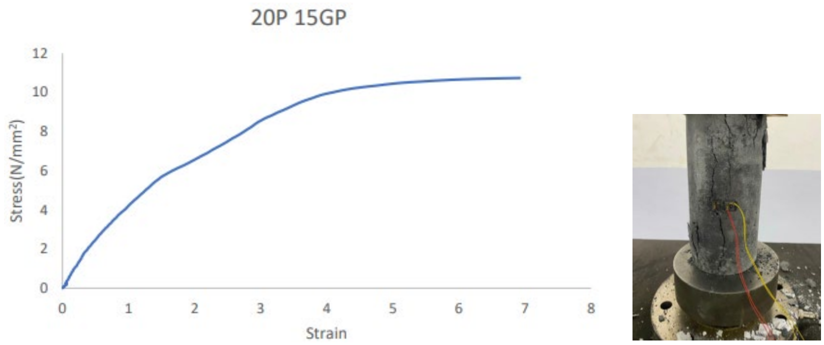


(a) **(b)**

Fig. 13 *(a) Stress vs strain 20P10GP; and (b) 20P10GP failure crack*

5.3.5 20P15GP Specimen

Similar to 20P10GP, this sample lacks a distinct elastic region and does not behave elastically. Fig.14(a) suggests that this sample is prone to developing microcracks under stress, with rapid crack propagation leading to premature failure, as shown in Fig.14(b). The absence of a clear elastic region indicates that the sample does not return to its original shape after the applied load is removed. Limited elastic deformation in concrete is attributed to its low tensile strength and brittle failure mode.



(a) **(b)**

Fig. 14 *(a) Stress vs strain 20P15GP, and (b) 20P15GP failure crack*

6. Conclusion

Increased GP proportions significantly reduce compressive strength. Both compressive strength and modulus of elasticity tests are influenced by cementitious materials, especially POFA and GP. The addition of 20% POFA generally enhances stiffness, while higher GP content has a pronounced reducing effect. SCC 20P 0G performs best, displaying higher compressive strength, MOE, and Poisson's ratio, indicating greater rigidity. SCC 20P 5G, with optimal GP proportion, shows slightly higher MOE and Poisson's ratio than the control sample. Higher GP proportions result in a significant drop in compressive strength, MOE, and Poisson's ratio, suggesting potential concerns for concrete mechanical behaviour. The changes in Poisson's ratio indicate variations in sample behaviour, with higher GP content suggesting a shift towards more brittle behaviour.

In conclusion, the analysis of mechanical properties in SCC mixes with partial cement replacement using POFA and GP reveals crucial insights. SCC 20P 0G, with 20% POFA and no GP, outperforms the control sample, showing remarkable increases in compressive strength and modulus of elasticity. However, caution is advised with higher GP concentrations in SCC 20P 10G and SCC 20P 15G, as they result in a decline in both properties and suggest potential brittle behaviour. These findings highlight the significant impact of supplementary materials on SCC properties, emphasizing SCC 20P 0G as promising for high strength and stiffness. Further research is recommended to uncover underlying mechanisms for optimal concrete formulations in diverse engineering applications.

Optimal mechanical properties are achieved with SCC 20P 0G, featuring a 20% POFA replacement with no GP. This mix outperforms control, displaying significant gains in compressive strength and modulus of elasticity. In contrast, SCC 20P 5G shows nuanced performance, with a slight early strength decrease but notable improvement in 28 days. This mix strikes a balance, making it promising for applications needing both early and long-term strength. The attributes of SCC 20P 5G emphasize the importance of precise mix proportions. Further research on SCC 20P 5G can offer insights into developing high-performance and sustainable concrete mixes in construction.

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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:*** *Wan Inn Goh, Qadir Bux alias Imran Latif;* ***data collection:*** *Yasmin Ramli;* ***analysis and interpretation of results:*** *Wan Inn Goh Yasmin Ramli, Sufian Kamaruddin;* ***draft manuscript preparation:*** *Yasmin Ramli, Qadir Bux alias Imran Latif. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Chen, C., Xu, R., Tong, D., Qin, X., Cheng, J., Liu, J., Zheng, B., Yan, L., & Zhang, Q. (2022). A striking growth of CO_2 emissions from the global cement industry driven by new facilities in emerging countries. Environmental Research Letters, 17, 044007. https://doi.org/10.1088/1748-9326/ac48b5

[2] Jaturapitakkul, C., Tangpagasit, J., Songmue, S., & Kiattikomol, K. (2011). Filler effect and pozzolanic reaction of ground palm oil fuel ash. Construction and Building Materials, 25, 4287-4293. https://doi.org/10.1016/j.conbuildmat.2011.04.073

[3] Barbosa, W., Ramalho, R. D'Paula, & Portella, K. F. (2018). Influence of gypsum fineness in the first hours of cement paste: Hydration kinetics and rheological behaviour. Construction and Building Materials, 184, 304-310. https://doi.org/10.1016/j.conbuildmat.2018.06.235

[4] Ghulam, K., & Ahmad, P. (2022). Oil palm economic performance in Malaysia and R&D progress in 2021. Journal of Palm Oil Research, 34, 185-218. https://doi.org/10.21894/jopr.2022.0036

[5] Neville, A. M., & Brooks, J. J. (1990). Concrete Technology. Longman Group Limited.

[6] Chindaprasirt, P., Jaturapitakkul, C., & Sinsiri, T. (2007). Effect of fly ash fineness on microstructure of blended cement paste. Construction and Building Materials, 21, 1534-1541. https://doi.org/10.1016/j.conbuildmat.2005.12.024

[7] Reddy Thumma, A. (2017). Experimental study on gypsum as binding material and its properties. The International Journal of Engineering and Science, 6, 1-15.

[8] Subramani, T., & Anbuchezian, A. (2017). Experimental study of palm oil fuel ash as cement replacement of concrete. International Journal of Application or Innovation in Engineering & Management, 6, 1-5.

[9] Gholhaki, M., kheyroddin, A., Hajforoush, M., & Kazemi, M. (2018). An investigation on the fresh and hardened properties of self-compacting concrete incorporating magnetic water with various pozzolanic materials. Construction and Building Materials, 158, 173–180.

[10] Lashari, M. H., Memon, N. A., & Memon, M. A. (2021). Effect of using nylon fibers in self compacting concrete (SCC). Civil Engineering Journal, 7, 1426–1436. https://doi.org/10.28991/cej-2021-03091734

[11] Franco, M., Schmidt, W., Hans-Carsten Kühne, & André, R. (2020). Influence of high-charge and low-charge PCE-based superplasticizers on Portland cement pastes containing particle-size designed recycled mineral admixtures. Journal of Building Engineering, 32, 101515–101515.

[12] Yoshioka, K., Tazawa, E. I., Kawai, K., & Enohata, T. (2002). Adsorption characteristics of superplasticizers on cement component minerals. Cement and concrete research, 32, 1507-1513.

[13] Plank, J., & Hirsch, C. (2007). Impact of zeta potential of early cement hydration phases on superplasticizer adsorption. Cement and concrete research, 37, 537-542.

[14] Bahedh, M. A., & Jaafar, M. S. (2018). Ultra high-performance concrete utilizing fly ash as cement replacement under autoclaving technique. Case Studies in Construction Materials, 9, e00202. https://doi.org/10.1016/j.cscm.2018.e00202

[15] Kamaruddin, S., Goh, W. I., Jhatial, A., & Lakhiar, M. (2018). Chemical and fresh State properties of foamed concrete incorporating palm oil fuel ash and eggshell ash as cement replacement. International Journal of Engineering and Technology, 7, 350-354. http://doi.org/10.14419/ijet.v7i4.30.22307.

[16] Shehab, H., Eisa, A., & Ahmed, W. (2016) Mechanical properties of fly ash based geopolymer concrete with full and partial cement replacement. Construction and Building Materials, 126, 560-565. https://doi.org/10.1016/j.conbuildmat.2016.09.059.

[17] ASTM C33 (2003). Specification for Concrete Aggregates. ASTM International.

[18] Chen, J. (2015). Water in cement paste: Its importance and implications. Materials, 8, 1744-1759.

[19] Aziz, M. A. A. (2019). Mechanical properties of self-compacting concrete incorporating POFA and eggshell powder as cement replacement. Beng Report, Universiti Tun Hussein Onn Malaysia.

[20] Sata, V., Jaturapitakkul, C., & Kiattikomol, K. (2004). Utilization of palm oil fuel ash in high-strength concrete. Journal of Materials in Civil Engineering, 16, 623-628. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:6(623)
[21] Khankhaje, E., Salim, M. R., Mirza, J., Hussin, M. W., & Rafieizonooz, M. (2016). Properties of sustainable lightweight pervious concrete containing oil palm kernel shell as coarse aggregate. Construction and Building Materials, 126, 1054-1065. https://doi.org/10.1016/j.conbuildmat.2016.09.010
[22] Han, B., Zhang, L., & Ou, J. (2017). Self-compacting concrete. In Han, B., Zhang, L., & Ou, J. (Eds.), Smart and Multifunctional Concrete Toward Sustainable Infrastructures. Springer, pp. 11-36. https://doi.org/10.1007/978-981-10-4349-9_2
[23] Kamarou, M., Korob, N., Kwapinski, W., & Romanovski, V. (2021). High-quality gypsum binders based on synthetic calcium sulfate dihydrate produced from industrial waste. Journal of Industrial and Engineering Chemistry, 100, 324-332. https://doi.org/10.1016/j.jiec.2021.05.006
[24] European Federation of Producers and Contractors of Specialist Products for Structures (2002). Specifications and Guidelines for Self-Compacting Concrete. EFNARC, Surrey, pp. 1-32
[25] ASTM C469/C469M-14 (2014). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. ASTM International.
[26] BS 1881: Part 116 (1983). Method for Determination of Compressive Strength of Concrete Cubes. British Standard Institution.
[27] BS 1881: Part 121 (1983). Method for Determination of Static Modulus of Elasticity in Compression British Standard Institution.