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Research Article

Physical and mechanical characteristics of lightweight POFA geopolymer concrete with timber clinker aggregate

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Abstract

The construction industry is seeking sustainable alternatives to traditional Portland cement-based concrete due to its environmental impact. Geopolymer concrete, using industrial byproducts as binders, offers a solution by reducing emissions and improving durability. However, challenges such as costly activators and energy-intensive curing processes limit its adoption. This research investigates the properties of wood ash (WA) lye activated blended geopolymer concrete incorporating sustainable timber clinker aggregate (TCA). A fixed liquid-to-binder ratio of 0.5 and an alkaline activator ratio of 3.0 were used in the mix design. The study focused on replacing conventional coarse aggregates with TCA to enhance sustainability. Key analyses included physical, mechanical, durability, environmental and cost efficiency assessments. Results showed that the replacement of natural granite with TCA led to reduction in the density of the concrete from 2063.13kg/m^3 to 1805.66kg/m^3 for 0% and 100% TCA, respectively. Strength also decreased as TCA content rose, attributed to lower density. Water absorption increased with TCA content, though all samples stayed within the 10% absorption limit set by BS882: 1992. Notably, the TCA60 specimen met ASTM C330 (2009) requirements for structural lightweight aggregate concrete. The development of wood ash lye activated lightweight binary blended geopolymer concrete incorporating timber clinker aggregate represents a potentially groundbreaking advancement in sustainable construction materials.

1. Introduction

The construction industry is in the midst of a paradigm shift as it seeks innovative, sustainable, and environmentally responsible building materials. Traditional Portland cement-based concrete, while tried and tested, poses considerable environmental challenges due to its high carbon footprint and substantial consumption of finite natural resources [1]. To address these concerns, researchers and industry experts are increasingly turning to geopolymer concrete, a sustainable alternative that provides multiple benefits, such as lower greenhouse gas emissions and improved durability.

Geopolymer concrete represents a revolutionary approach to conventional concrete. It substitutes Portland cement with a geopolymer binder, typically derived from industrial byproducts like fly ash, slag, or metakaolin, which serve as the primary source of the reactive alumina-silica components [2]. The geopolymerization process entails dissolving these materials in an alkaline solution, leading to the formation of a three-dimensional network of silicate and aluminate species, creating a binder similar to traditional Portland cement but with distinct environmental benefits [3]. Geopolymer concrete has gained prominence in recent years due to its sustainability advantages. It notably reduces carbon emissions as the production of the geopolymer binder

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requires less energy and generates fewer greenhouse gases than Portland cement. Furthermore, geopolymer concrete displays exceptional resistance to various forms of deterioration, including chemical attacks, alkali-silica reactions, and sulfate attacks, making it an attractive choice as normal weight and lightweight concrete for enduring and resilient construction projects [4]. Recognizing the environmental concerns linked with conventional lightweight concrete, researchers have turned to geopolymer technology to develop lightweight geopolymer concrete. By replacing Portland cement with a geopolymer binder, it becomes possible to create lightweight concrete with significantly reduced carbon emissions and a lower environmental footprint.

Extensive study has been conducted on geopolymer concrete as a possible substitute for traditional Portland cement concrete. However, despite its promising advantages, the adoption of geopolymer technology is primarily limited to laboratory settings and has not been widely implemented in the field. This limitation is mainly due to challenges such as the use of chemical activators and the need for energy-intensive oven curing. To address these challenges, researchers have explored the use of agricultural and industrial by-products like palm oil fuel ash (POFA), wood ash (WA), and ground granulated blast furnace slag (GGBS) in the production of geopolymer concrete.

POFA is derived from burning the residue of the oil extraction process from fresh palm fruits, which is typically discarded in open fields, leading to environmental and health issues. In Malaysia, it is estimated that about 10 million tons of POFA are produced annually [5]. However, most studies have focused on activating POFA-based geopolymers using sodium hydroxide (NaOH) or potassium hydroxide (KOH), which raises production costs [6,7,8]. It is imperative to examine the use of more economical substitutes, such as WA lye, a strong alkaline solution, as a replacement for the expensive chemical activators often employed in the production of geopolymer concrete. Another sustainability issue facing in the concrete sector is the depletion of natural resources, which poses a significant environmental concern. The ongoing extraction of naturally existing rocks for coarse aggregates may ultimately result in their exhaustion [9]. To address this issue, many researchers have turned their attention to using waste materials like palm oil clinker aggregate (POCA), recycled concrete aggregate (RCA), timber clinker aggregate (TCA), and palm oil shell (POS) as alternatives in concrete production. Among these, TCA has begun to gain attention as a supplementary material to replace natural aggregates in concrete manufacturing.

Integrating TCA into lightweight geopolymer concrete offers a novel and innovative method for improving its properties. Timber clinker is a material produced through the thermal treatment of wood waste, including wood chips and sawdust. This clinkering process subjects wood waste to high temperatures in the absence of oxygen, leading to the formation of high-strength, porous, and lightweight aggregates. Incorporating TCA into geopolymer concrete offers several potential benefits. Firstly, it allows for the use of abundant wood waste materials, which are typically underutilized in the construction industry. This promotes the recycling and repurposing of wood waste, reducing the environmental impact associated with its disposal. Additionally, TCA are known for their low thermal conductivity, making them an ideal choice for enhancing the thermal insulation properties of lightweight geopolymer concrete. Furthermore, the porous structure of TCA has the potential to improve the lightweight properties of the concrete, which can be particularly advantageous in applications where weight reduction is critical.

According to a previous study by Chai et al. [10], concrete incorporating TCA demonstrated high compressive strength, reduced void content, and lower water permeability. Additionally, adding TCA improved the durability of concrete, with a maximum replacement level of up to 20%. Utilizing timber clinker aggregates not only enhances concrete performance but also promotes sustainability by recycling wood waste. Meanwhile, there is limited study on the application of TCA as a replacement for natural aggregate in geopolymer concrete. As such, it is still lack of comprehensive understanding on the effect of TCA on the physical and mechanical properties of geopolymer concrete. Therefore, this study aims to evaluate the potential of TCA as a partial replacement for natural aggregate in geopolymer concrete. Additionally, the effectiveness of WA lye in activating POFA geopolymer concrete is also being study. By adopting geopolymer technology and incorporating TCA and WA lye as activator, this research highlights a commitment to reducing the environmental impact of construction materials. It explores the transformation of wood waste into high-strength aggregates, providing an innovative solution for recycling abundant wood waste. This approach aligns with circular economy principles, emphasizing efficient resource use and waste minimization.

2. Materials and Methods

2.1. POFA

The research utilized POFA sourced from an oil mill located in Nibong Tebal, Pulau Pinang, Malaysia. This POFA is a byproduct resulting from the combustion of materials like husk and shells, which are burned to generate steam for use in a turbine engine for electricity generation, as reported by Salam et al. [11]. The factory's report indicated that the end product was incinerated within a temperature range of 400 to 500℃. The collected POFA was subjected to oven drying at 105 ± 5℃ for a duration of 24 hours. Following this, it was passed through a 300µm sieve and then milled using a ball mill for 2 hours, resulting in an ash with a particle size of approximately 80% passing through a 45µm sieve. This meet the requirements specified in ASTM C618 [12], and the specific gravity of the POFA was determined to be 2.40. The Blaine fineness test was conducted to determine the specific surface area in accordance with BS EN 196-6 (2010), and POFA was found to have a Blaine surface area of 4433.7 cm^2/g. The chemical composition of the POFA utilized in the study is presented in Table 1.

2.2. GGBS

In this research, GGBS was used as the high-calcium binding agent. The GGBS used was sourced from MDC Sdn. Bhd. in Kedah, Malaysia, and it had a specific gravity of 2.80. The chemical composition of the GGBS employed in the study can be found in Table 1.

2.3. Alkaline Activator

WA lye, derived from waste wood ash, a byproduct of wood industry operations, is an abundant and environmentally friendly alternative. It offers a 100% cost-effective solution while posing fewer health risks to humans compared to NaOH. In this study, WA lye with a high pH level of 13.16, was utilized alongside sodium silicate as an alkaline activator in the geopolymer concrete production process. The chemical composition of the WA used is detailed in Table 1. The total SiO_2, Al_2O_3, and Fe_2O_3 content is 62.21%; hence, the untreated POFA is classified as class C pozzolana by ASTM C618 [12]. In addition, the XRF study reveals that GGBS constitutes 32.79% of CaO. Additionally, it was discovered that the WA utilized contained a significant amount of K_2O. Fig. 1 shows the XRD patterns of WA, POFA, and GGBS.

Table 1. Chemical composition of POFA, GGBS and WA

Oxide compounds	Composition (%)		
	WA	POFA	GGBS
MgO	8.24	5.02	6.38
Al2O3	3.01	3.27	14.62
SiO_2	12.06	54.98	30.35
SO3	2.55	4.09	-
Cl	0.04	1.78	-
K2O	10.15	9.50	0.38
CaO	55.01	10.77	32.79
Cr_2O_3	0.02	-	-
MnO	1.29	0.14	0.45
Fe2O3	2.92	3.96	0.35
ZnO	0.03	-	-
SrO	0.11	-	-
AS2O3	0.01	-	-
CuO	0.02	-	-
Rb2O	0.01	-	-
NiO	0.02	-	-

Na2O	0.14	0.40	0.27
P_2O5	4.01	5.64	0.01
Ga_2O_3	0.01	-	-
Y2O3	0.01	-	-
ZrO2	0.01	-	-
TiO_2	-	0.19	0.57
BaO	0.04	-	-
LOI	-	5.66	-

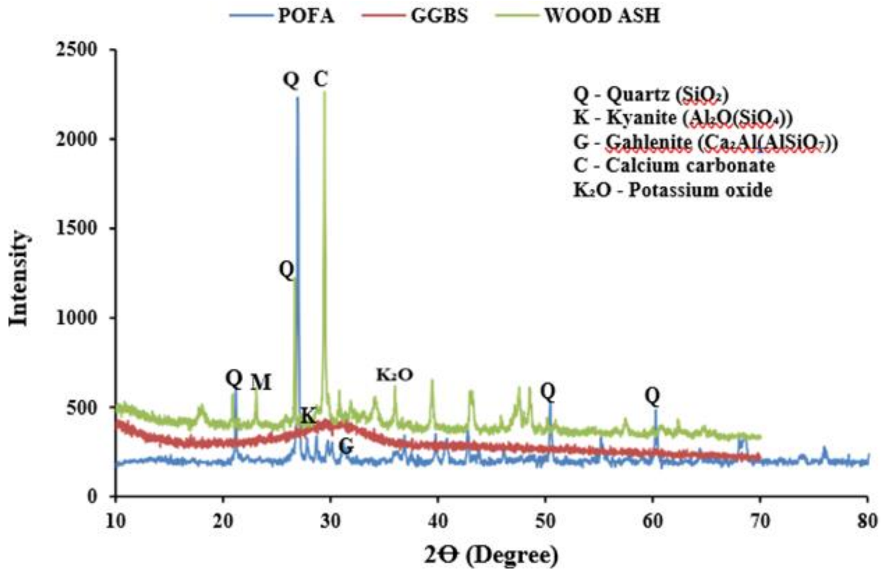

Fig. 1. XRD patterns of POFA, WA and GGBS

2.4. Aggregate

2.4.1 Fine Aggregate

The research employed fine aggregate sourced from local suppliers, which was river sand. This sand underwent sieving through a 4.75mm sieve and possesses a specific gravity of 2.63. The sand was subjected to sieve analysis in accordance with ASTM C136 [13], and Fig. 2 provides a visual representation of the sieve analysis results. The cumulative percentage passing of the river sand was compared to ASTM C33 [14] and found to be within the specified finer and coarser limits for fine aggregate as shown in Table 2.

Table 2. Sieve analysis of river sand

Sieve size	ASTM C33	Percent Passing
10mm	100	100
4.75mm	95 – 100	100
2.36nm	80 – 100	84.1
1.18nm	50 – 85	51.7
600µm	25 – 60	20.8
300µm	5 - 30	7.40
150µm	0 - 10	1.60
75µm	-	0.34
Pan	-	0

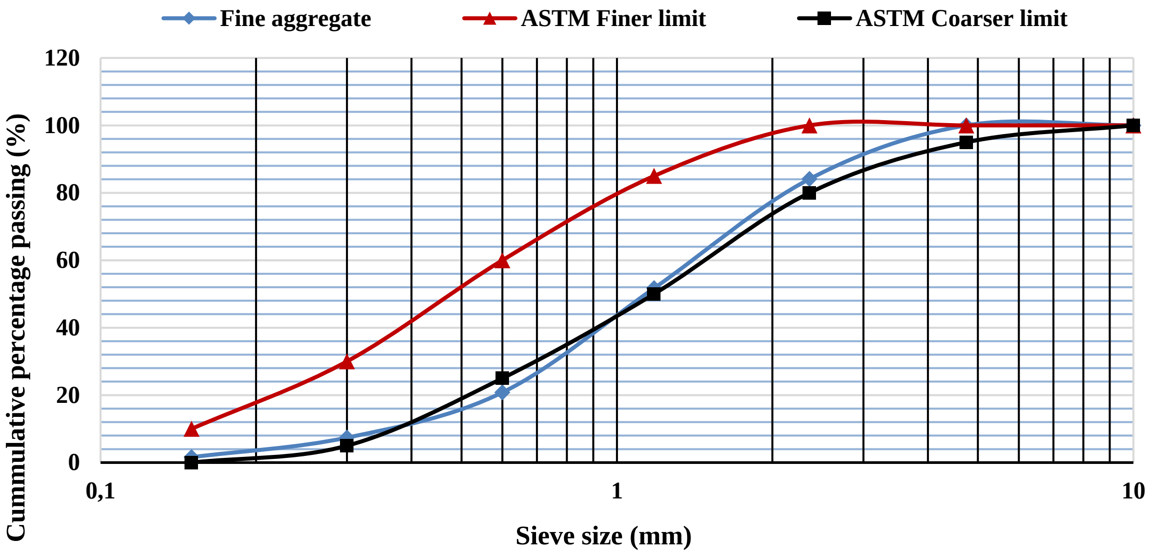

Fig. 2. Sieve analysis of river sand

2.4.2 Natural aggregate

The study utilized coarse aggregate sourced from local suppliers, consisting of 12mm diameter crushed granite. This aggregate exhibited fundamental attributes of an excellent coarse aggregate, including low porosity, strong crushing resistance, and minimal water absorption. Table 3 summarizes the physical characteristics of this crushed granite aggregate, while Fig. 3 presents the sieve analysis graph for the crushed granite.

2.4.3 Timber clinker aggregate (TCA)

TCA is another outcome of burning wood in boilers for the purpose of generating electricity. Typically, it appears as chunky clinkers and is frequently discarded in landfills. These clinkers are crushed to achieve the preferred size of 12mm, which is then used as coarse aggregate (as depicted in Fig. 4). The physical characteristics of this TCA, encompassing factors like specific gravity, aggregate crushing value, and water absorption, are detailed in Table 3. Furthermore, Fig. 3 illustrates the sieve analysis results for the TCA employed in this research.

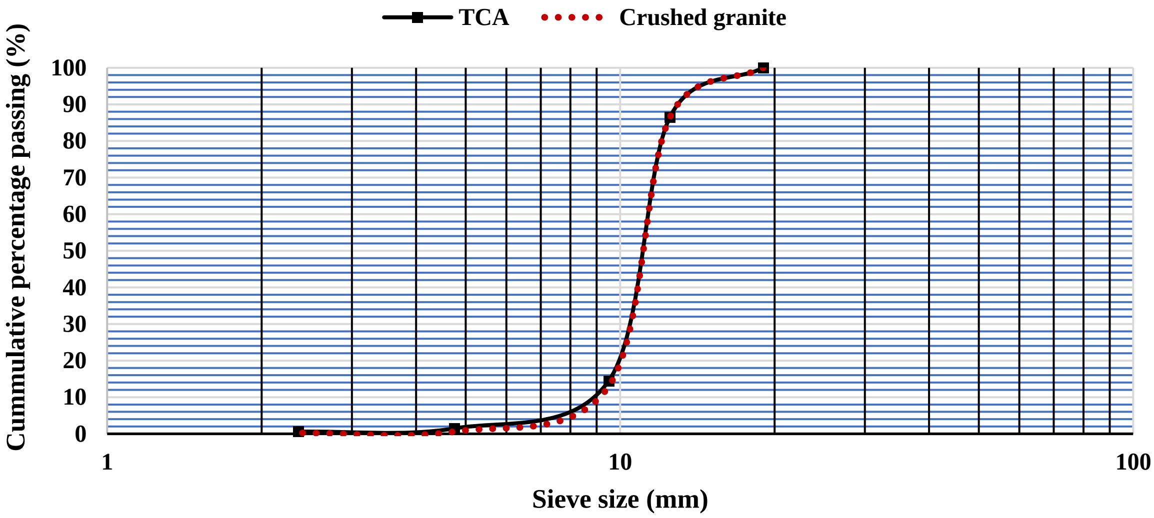

Fig. 3. Sieve analysis graph of natural granite and TCA

Table 3. Physical properties of coarse aggregates

Properties	Crushed Granite	Timber Clinker	Standards
Specific Gravity	2.64	2.10	IS 383: 1970
Water Absorption	0.81%	2.31%	BS 882: 1992
Aggregate Crushing Value	19%	22%	BS 882: 1992

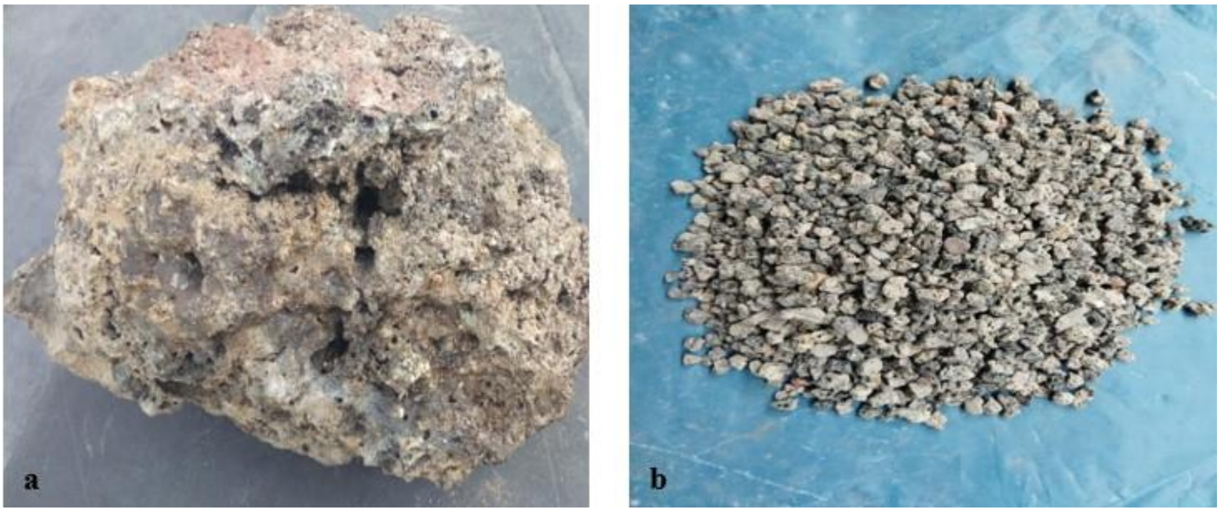

Fig. 4. (a) Timber clinker chunk (b) Crushed timber clinker aggreate (12mm)

2.5. Preparation and Curing of Specimen

The alkaline activator in this study was created by combining water and sieved WA at a specific ratio of 1:2. This mixture was left undisturbed for several days until it reached a pH of 13.16. The authors employed a liquid-to-binder (L/B) ratio of 0.5 and an alkaline activator ratio (AAR) of 3.0, based on findings from their earlier research. Cube size of 100 x 100 x 100mm were produced and subjected to compression tests at various time intervals (3, 7, 14, 28, 56, and 180 days). Additionally, cylindrical specimens measuring 100 x 200mm for split tensile strength tests and 100 x 100 x 500mm beams for flexural strength tests were produced. The workability of the fresh geopolymer concrete was assessed through a slump test.

Table 4. Geopolymer concrete mix proportion

TCA Content (%)	POFA (kg/m^3)	GGBS (kg/m^3)	Sand (kg/m^3)	Natural Gravel (kg/m^3)	TCA (kg/m^3)	Lye (kg/m^3)	Na_2SiO_3 (kg/m^3)
0	315.00	135.00	756.70	888.30	0.00	56.25	168.75
20	311.59	133.54	494.78	710.64	135.50	55.64	166.90
40	311.59	133.54	494.78	532.98	271.01	55.64	166.90
60	311.59	133.54	494.78	355.32	406.51	55.64	166.90
80	311.59	133.54	494.78	177.66	542.02	55.64	166.90
100	311.59	133.54	494.78	0.00	677.52	55.64	166.90

The specific mix proportions for the binary blended lightweight geopolymer concrete with TCA can be found in Table 4. An epicyclic mixer, conforming to ASTM C305 [15] was employed to prepare the geopolymer concrete mix. Initially, POFA and GGBS were dry mixed for about 3 minutes to achieve a uniform consistency. Next, the alkaline activator was added, and the mixture was stirred for an additional 6 minutes to form a three-dimensional geopolymer network. Following this, aggregates were added and mixing continued for another 5 minutes. The prepared mixture was then poured into molds and vibrated to ensure proper compaction. The specimens were wrapped in plastic to prevent moisture loss and left to set for 24 hours before demolding. After demolding, the specimens are cured at ambient conditions, maintaining a temperature of 25°C ± 5°C and a relative humidity of 75% ± 5%.

2.6. Testing Methods

2.6.1. Slump Test

The workability of the geopolymer concrete was evaluated using the conventional slump test in accordance with ASTM C143 [16]. The test involved filling a metal cone with concrete in three layers, with each layer tamped 25 times using a metal rod as shown in fig. 5. After filling, the cone was carefully lifted, and the slump was measured as the distance from the top of the slumped concrete to the top of the inverted cone.

Fig. 5. Slump test

Fig. 6. Compressive Strength Test

2.6.2. Compressive Strength

The compressive strength test was performed using a GOTECH GT-7001-BS300 machine with a capacity of 3000 kN, in accordance with BS EN 12390-3 [17] as shown in Fig. 6. The compressive strength of the mortar was tested at 3, 7, 14, 28, 56, and 180 days.

2.6.3. Flexural and Tensile Strength

For concrete prisms of size 100 x 100 x 500mm, the flexural strength test was conducted according to ASTM C293 [18] using ELE universal testing machine as shown in Fig. 7.

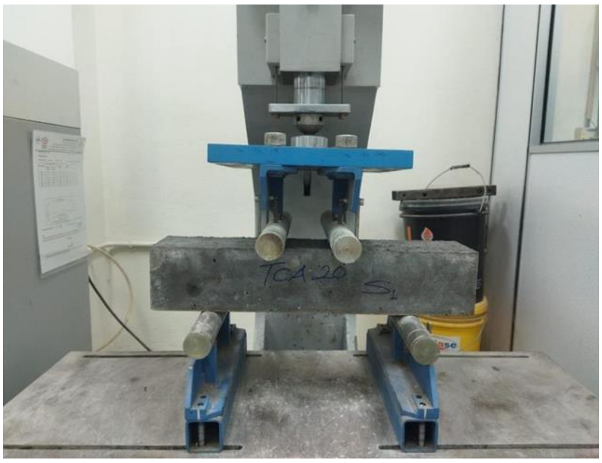

Fig. 7. Flexural Strength Test

Fig. 8. Tensile Strength Test

The tensile strength test for lightweight geopolymer concrete was conducted using cylindrical specimens with a diameter of 100mm and height of 200mm, following ASTM C496 [19]. The test was performed on a GOTECH GT-7001-BS300 machine with a 3000kN capacity, in accordance with BS EN 12390-3 [20] (Fig. 8). The tensile strength was measured at 3, 7, 14, 28, 56, and 180 days.

2.6.4. Ultrasonic Pulse Velocity (UPV) Test

The ultrasonic pulse velocity (UPV) test, a non-destructive test, was conducted on 100mm x 100mm x 100mm concrete cubes before the compressive strength tests at 3, 7, 28, 56, and 180 days. This test followed the MS EN 12504-4 [21] standard, using the Proceq Tico ultrasonic instrument as shown in Fig. 9.

Fig. 9. UPV Test

Fig. 10. Water Absorption Test

2.6.5. Water Absorption

The water absorption test was performed on cylindrical specimens measuring 75 mm in diameter and 100 mm in length, following ASTM C642 [22], as illustrated in Fig. 10. The water absorption percentage was determined by subtracting the oven-dry weight of the sample from its saturated weight, dividing this difference by the oven-dry weight, and multiplying by 100.

2.6.6. Drying Shrinkage

The drying shrinkage measurement was carried out according to ASTM C157 [23] as shown in Fig. 11. The drying shrinkage test was conducted at intervals of 3, 7, 14, 28, 56, 90, 180, and 270 days to track changes in specimen length over time.

Fig. 11. Drying Shrinkage Test

Fig. 12. Sulphate Resistance Test

2.6.7. Sulphate Resistance

Sulphate resistance test is conducted following ASTM C1012-04 [24]. Concrete cubes measuring 100mm x 100mm x 100mm were produced and cured at ambient temperature for 28 days before being exposed to a 5% magnesium sulfate ($MgSO_4$) solution for up to 180 days (Fig. 12). The solution was prepared by dissolving 1000g of $MgSO_4$ in 10 liters of water to achieve the desired concentration, with the solution changed monthly. Durability was assessed by monitoring mass change and residual compressive strength at intervals of 0, 28, 56, and 180 days of immersion. The compressive strength of the immersed specimens was compared to control specimens cured at ambient temperature for the same duration.

3. Results and Discussions

3.1. Workability

The workability of the geopolymer concrete was assessed by measuring the slump, and the outcomes are depicted in Fig. 13. An observable decrease in the slump height was noted as the content of TCA increased within the mixture. This phenomenon can likely be attributed to the superior water absorption capacity of TCA in comparison to conventional aggregates, as corroborated by the research of [25], which compares palm oil clinker aggregate (POCA) with conventional aggregates, noting higher water absorption of POFA that reduces slump height. This suggests that mixtures with higher TCA content tend to absorb more of the alkaline solution compared to control mixes with lower TCA content. The highest slump measurement of 115mm was achieved in the TCA0 mix, while subsequent increments of 20% TCA content resulted in an approximately 18% reduction in the slump height, with the lowest value of 43mm attained by the TCA100 mix.

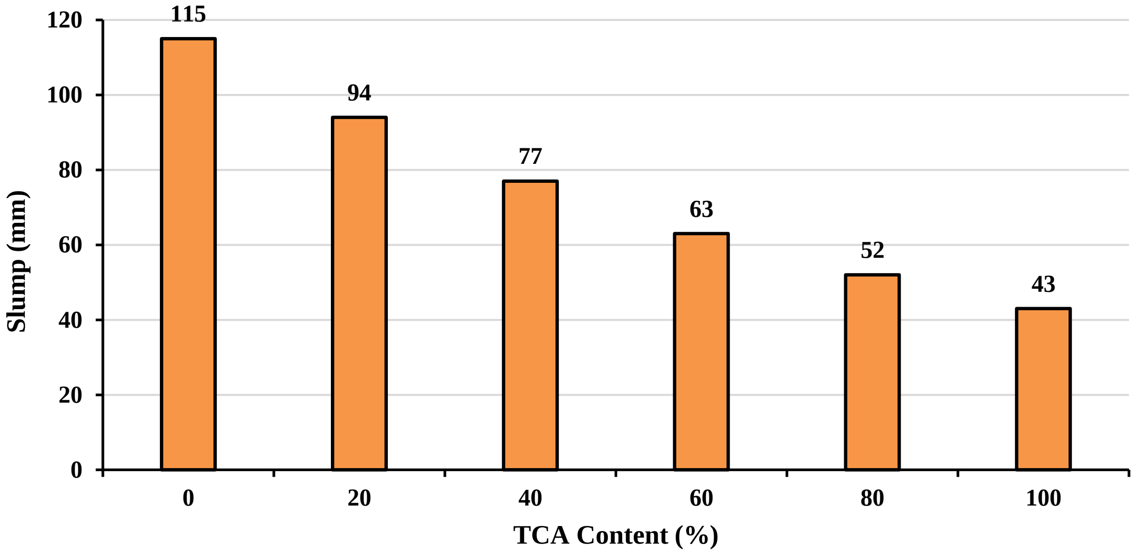

Fig. 13. Workability result of binary blended POFA:GGBS geopolymer concrete incorporating TCA

In this experimental research, to prevent any dilution effects against the WA lye, additional water or superplasticizers were intentionally not utilized. Unlike Ordinary Portland Cement (OPC) concrete, where superplasticizers can notably enhance material performance, their use in geopolymer binders typically has minimal to no discernible impact. This is due to the tendency of the alkaline solution to degrade the superplasticizer and diminish its effectiveness, as noted in the literature [26]. Notably, in lightweight geopolymer concrete, it was observed that the alkaline solution tends to enhance the workability of the mixture [25]. This observation was reaffirmed in this research, where a moderate to high workability was achieved without the need for extra water or superplasticizers.

Another contributing factor affecting the workability of the geopolymer concrete is the shape of the TCA, which is angular and rough in contrast to natural aggregates. Rehman et al. [26] reported that using rounded aggregates in concrete results in a higher slump. However, in this research, the angular shape of the aggregate appeared to create a frictional effect that hindered particle movement, consequently reducing the flowability of the concrete. Similar findings were also documented by Rehman et al. [27].

3.2. Density

The 28-day density of geopolymer concrete containing TCA is depicted in Fig. 14 below. According to ASTM C330 [28] structural lightweight concrete typically falls within the density range of 1440 - 1840 kg/m^3 when 100% lightweight aggregate is used. The density of lightweight concrete is influenced by the unit weight of the aggregate, as affirmed by Malkawi et al. [25], owing to their higher proportion in the concrete mix. The bulk density of the TCA employed in this experimental study is lower than that of natural aggregates, which implies an expected reduction in the concrete density when TCA partially replaces natural aggregates.

The analysis of the experimental results shows a consistent reduction in the density of the geopolymer concrete with the addition of TCA. The 28-day density of specimens with normal aggregates measured at 2063.13 kg/m^3, followed by the 20% TCA specimens with a density of 1960.97 kg/m^3, indicating an approximate 4.95% reduction in density. The specimens featuring 100% TCA recorded a density of 1805.66 kg/m^3, marking an approximate 12.48% reduction in density when compared to the control specimens. Notably, it is worth mentioning that specimens with 100% TCA content fall within the range specified by ASTM C330 [28] for structural lightweight concrete, making them suitable for various structural lightweight concrete applications.

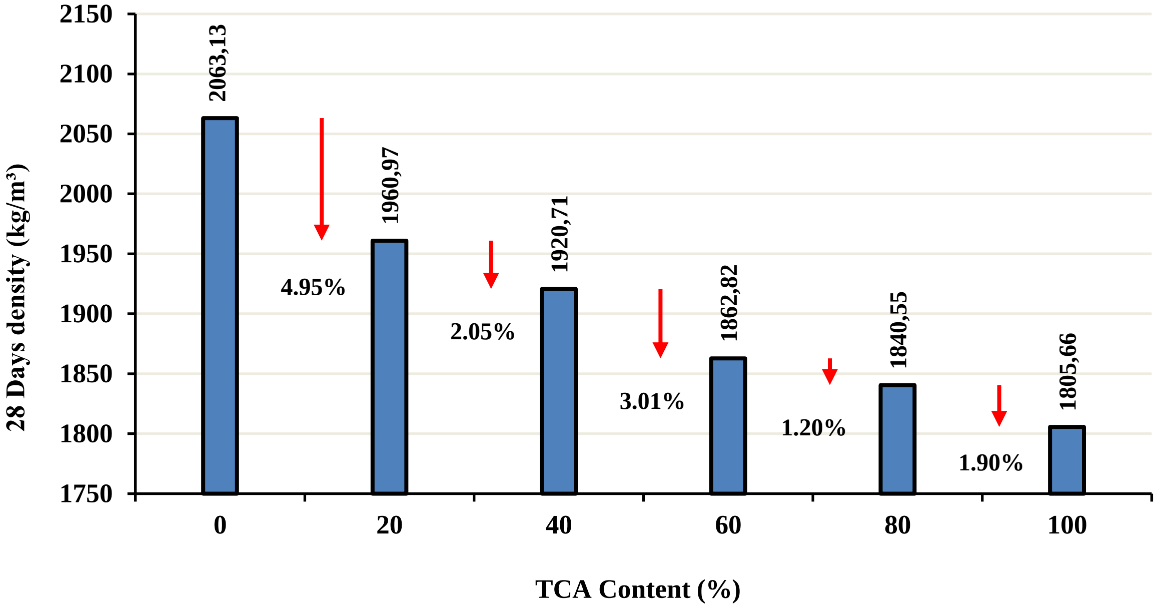

Fig. 14. Average density of binary blended POFA: GGBS geopolymer concrete incorporating TCA at 28 days

3.3. Compressive Strength

Fig. 15 shows the compressive strength results of POFA geopolymer concrete incorporating TCA at different replacement percentages for natural aggregate. A noticeable trend emerges, where the substitution of natural aggregate with TCA leads to both a reduction in density and a decline in the concrete's compressive strength. This outcome can likely be attributed to the relatively lower strength and bulk density of lightweight aggregates compared to their natural counterparts; a finding that is consistent with the research conducted by Malkawi et al. [25]. Given the gradual development of strength in geopolymer concrete cured under ambient conditions, the early strength measurements were only around 50% of the 28-day strengths. However, these concrete mixes continue to gain strength as the curing period progresses.

Analyzing the test results, it becomes evident that the control specimen achieved the highest strength of 28.78 MPa at 3 days, while a consistent reduction in strength is observed in the TCA specimens, with reductions of 20.74%, 32.59%, 42.84%, 48.75%, and 57.61% for 20%, 40%, 60%, 80%, and 100% TCA content, respectively. After 28 days of ambient curing, the control specimen retained approximately 88.40% of its 180-day strength, a trend also observed in the remaining TCA specimens, which attained approximately 88% to 90% of their 180-day strength at 28 days. This sustained strength development over the curing period is possibly attributed to the water absorbed by the porous TCA, which is subsequently released, triggering the hydration reaction [27].

Chai et al. [10] conducted a study on the effects of TCA in concrete, showing that incorporating TCA up to a 20% replacement level improved the durability and compressive strength, while higher TCA contents negatively impacted compressive strength. This indicates that moderate levels of TCA can balance strength and sustainability, but excessive replacement reduces workability and strength due to high water absorption. This is also proven by the study of Malkawi et al. [25], which explored the use of palm oil clinker aggregate (POCA), another lightweight aggregate, in geopolymer concrete, observing that increasing POCA content reduced density and compressive strength. Similar to TCA, the lightweight nature and porosity of POCA contributed to a decline in strength, but it also provided advantages in terms of lower thermal conductivity and reduced overall concrete weight.

Furthermore, it was observed that the loss of strength was more pronounced at higher levels of TCA replacement. This could be attributed to the reduced workability of the specimens, making them somewhat challenging to compact. Malkawi et al. [25] reported that a higher content of lightweight aggregates resulted in the absorption of the alkaline solution in the mixture, which, in turn, left some of the binder particles unreacted. This factor may also contribute to the reduction in strength of geopolymer concrete when incorporating TCA in comparison to specimens using natural aggregates.

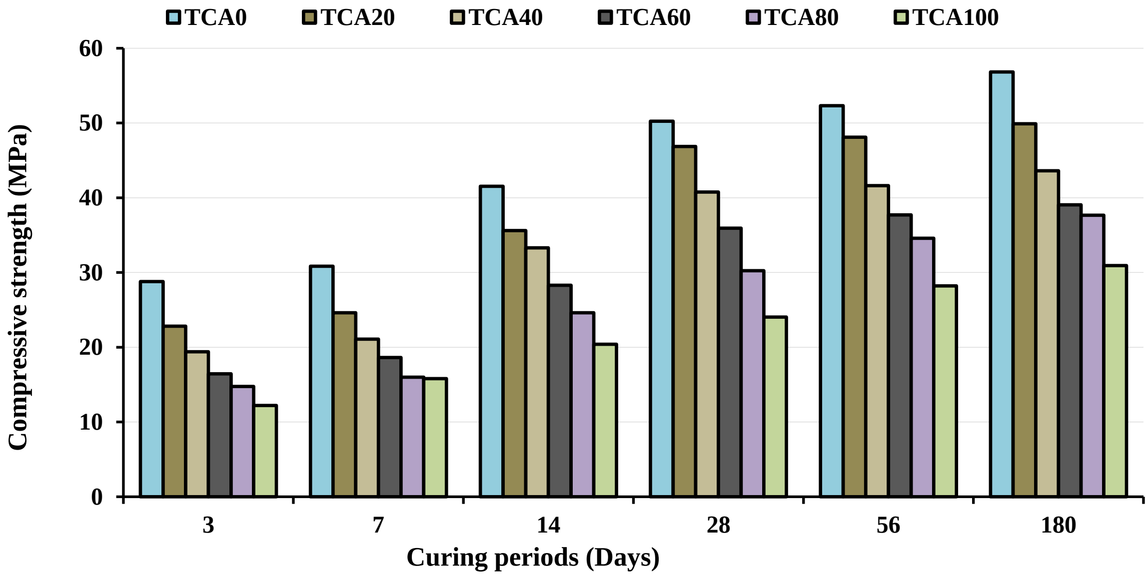

Fig. 15. Compressive strength of binary blended POFA:GGBS geopolymer concrete incorporating TCA

The compressive strength of lightweight geopolymer concrete is closely related to its density. Generally, higher-density concrete exhibits greater compressive strength. Fig. 16 illustrates the relationship between the density at 28 days and the corresponding compressive strength at the same curing age. The addition of TCA in the geopolymer concrete reduced its density, which in turn lowered the compressive strength.

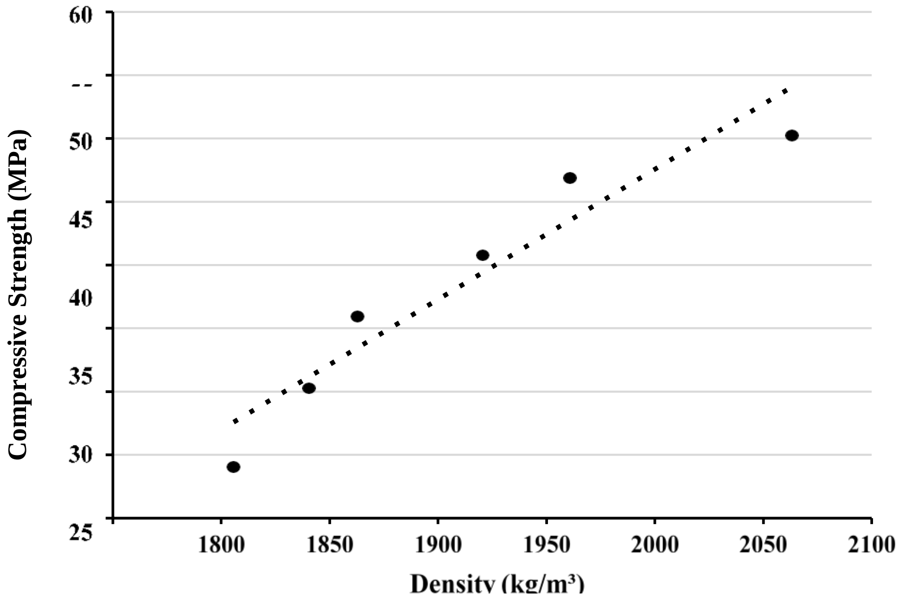

Fig. 16. Relationship between compressive strength and density at 28 days of curing

3.4. Flexural and Tensile Strength

The flexural strength of different replacements of TCA in binary blended POFA: GGBS geopolymer concrete was tested at 3, 7, 14, 28, 56, and 180 days, respectively. Referring to the test result (Fig. 17), the flexural strength of the geopolymer concrete decreases with increasing percentages of TCA in the mixture. The percentage reduction in the flexural strength at 28 days as compared to the control sample were 2.94, 5.48, 8.61, 16.83, and 25.44% for 20, 40, 60, 80, and 100% TCA, respectively. Malkawi et al. [25] reported that failure in tension generally occurs due to the breakdown of binder-aggregate bond. This was observed to create the presence of voids in the concrete which caused stresses concentration and let to cracks propagation. In this experimental study, the presence of voids was noticed in concrete with TCA content as shown in Fig. 18, this explains the reduction in the flexural strength of the TCA concrete specimens. Moreover, it was reported that the lower crushing value of lightweight aggregates (LWA) has very little or no impact on concrete's flexural strength [25]. This was due to fact that the compression zone in concrete beam specimen have an insignificant effect on bending failure [29].

Referring to the results of the tensile strength in this study (Fig. 19), the inclusion of TCA in the concrete reduced the strength of concrete. A tensile strength of 3.92MPa was attained by the control specimens at 28 days, a subsequent decrease in the concrete's strength was recorded for 20, 40, 60, 80, and 100% TCA concretes with approximately 3.74, 3.63, 3.31, 2.67, and 2.54MPa, respectively. The decline in the split tensile strength may be due to the porous nature of TCA which results in higher water absorption compared to control specimens [20]. This finding was also noted in this study where the specimens with TCA possessed higher water absorption compared to control specimens. Also, the voids presence in the concrete as shown in Fig. 18 contributed to the stresses concentration which hastened the development of cracks in the concrete. As opposed to compression strength, where the matrix and aggregate support one another as a result of the compressive pressures, the aggregates and matrix are separated apart under the action of tensile forces [27]. It was also reported that lightweight aggregate utilization in concrete usually led to a high reduction in the split tensile strength and elastic modulus compared to compressive strength [31]. It is worth mentioning that all lightweight geopolymer concretes produced with TCA in this study meets the 28 days minimum tensile strength requirement of 2.0MPa [28]. Hence TCA can effectively be utilized as an aggregate in structural lightweight concrete.

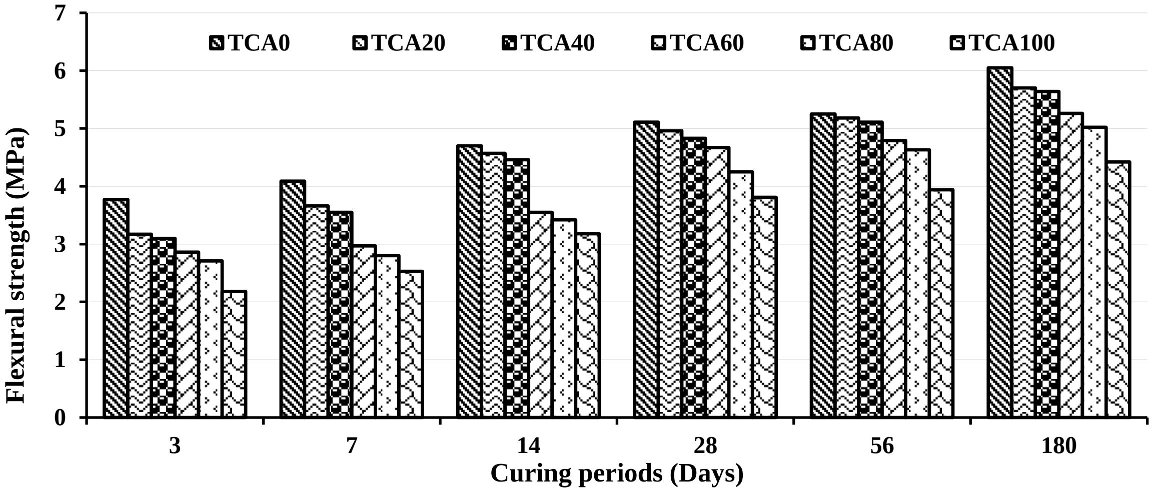

Fig. 17. Flexural strength of binary blended POFA: GGBS geopolymer concrete incorporating TCA

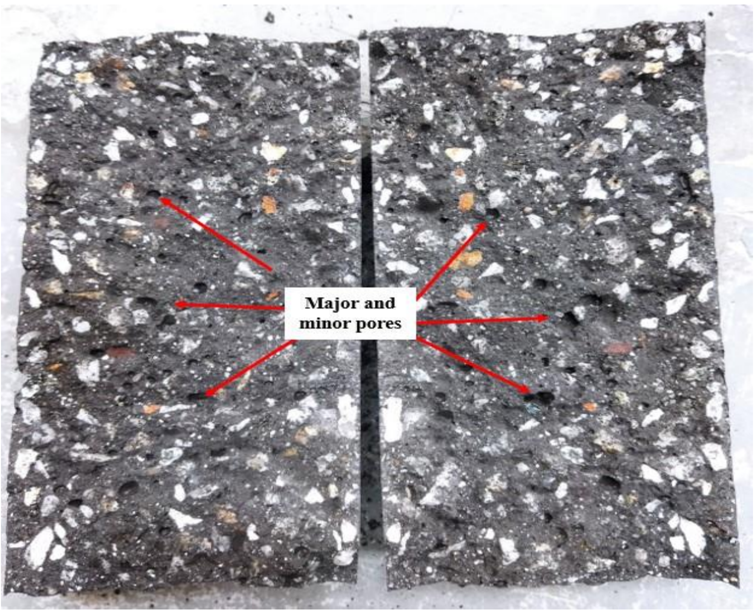

Fig. 18. TCA specimen with arrows showing pores in concrete

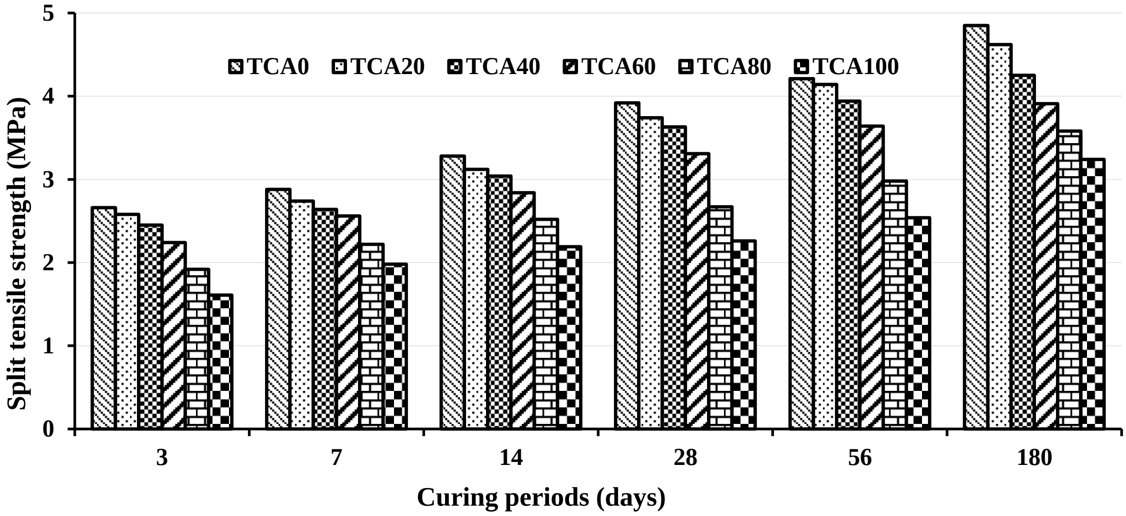

Fig. 19. Split tensile strength of binary blended POFA: GGBS geopolymer concrete incorporating TCA

3.5. Ultrasonic Pulse Velocity

Quality of concrete and its internal structure like micro pores, homogeneity, and cracks can be assessed using UPV non-destructive test. This test relates concrete's quality to ultrasonic pulse speed dispersed through the concrete from one transmitter to the other. The higher of the pulse's speed indicates the quality of the concrete and vice versa. UPV test was carried out in this experimental study at 7, 28, 56, and 180 days, respectively.

The UPV test results of the binary blended POFA: GGBS geopolymer concrete incorporating TCA are illustrated in Fig. 20 below. It can clearly be observed that the inclusion of TCA in the concrete decreased the UPV readings, this was already anticipated because TCA inclusion creates more pores in the concrete as compared to control specimens. It was established that the increase in the number of micro pores in concrete reduced the speed of the pulse which results in low readings. However, for all the samples tested, the UPV increased gradually as the curing period increases, indicating a gradual refinement in the micropore structures of the concrete with the increase in the curing duration. The reduction in the micro pores may be due to the ongoing geopolymerization reaction creating extra C-A-S-H gel which solidifies the concrete over time.

Referring to the test results presented, the control specimen exhibited the highest UPV readings of 3930, 4135, 4170, and 4504 m/s at 7, 28, 56, and 180 days, respectively. These were 26.77, 27.09, 25.90, and 29.51% compared to 100% TCA specimens. It is worth mentioning that all the concrete specimens tested fall within the category of medium – excellent concretes [32].

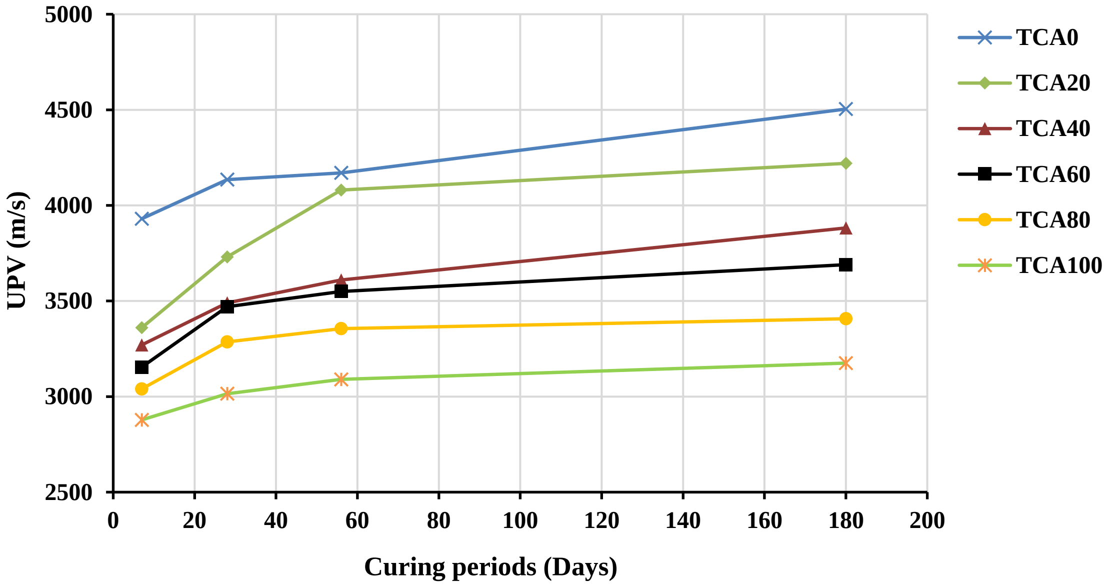

Fig. 20. Effect of TCA inclusion on UPV

3.6. Water Absorption

Water absorption in concrete is an indication of pore volume within the specimen. According to BS 1881 [33], a maximum water absorption of 10% is acceptable for various construction applications, including structural elements, minor structural elements, and non-structural elements. In this phase of the study, the water absorption was taken as an average of three specimens at 3, 7, 14, 28, 56, and 180 days. Fig. 21 displays the average results for various percentages of TCA inclusion in the concrete as a partial replacement for coarse aggregate. The addition of TCA to the concrete results in higher water absorption, which aligns with expectations given its porous nature. Ahmad et al. [34] also reported that the elevated water absorption in lightweight concrete is mainly governed by the porosity of the lightweight aggregates. Other researchers have reported similar findings, indicating that lightweight concrete typically exhibits higher water absorption compared to normal weight concrete [35, 36].

Referring back to the result of this study, it was observed that the water absorption of all the specimens decreases with the prolong curing period which was possibly due to the gradual refinement of the micro pores in the concrete as a result of continuous geopolymerization process over time. However, the observed trend in water absorption aligns with the typical pattern reported in the literature, where the absorption rate increases with the proportion of lightweight aggregate in the concrete. The 28-day water absorption for the control concrete (TCA0) was measured at 4.59%. With the addition of TCA at replacement levels of 20%, 40%, 60%, 80%, and 100%, the water absorption values increased to 5.02%, 5.38%, 5.75%, 6.02%, and 6.52%, respectively. These results are consistent with previous studies on POFA geopolymer concrete with natural aggregates, which typically show water absorption rates below 10%, remaining within the acceptable limits specified by standards such as BS882:1992 [37]. In summary, it is notable that all tested specimens stayed below the 10% maximum water absorption limit set by BS 882:1992, indicating compliance with standard requirements for water absorption.

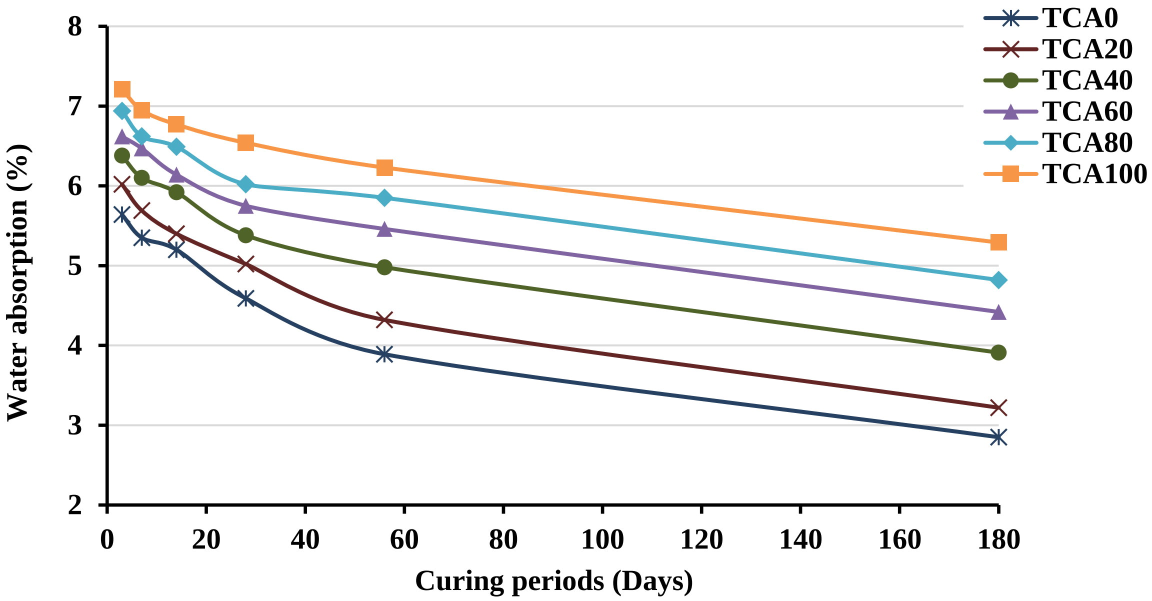

Fig. 21. Effect of TCA inclusion on water absorption

3.7. Drying Shrinkage

The drying shrinkage was calculated as the average of two beams, with changes in length recorded over a period of 270 days, as shown in Fig. 22. Based on the drying shrinkage results from this study, it was observed that increasing the TCA content in the mixture resulted in higher water absorption and porosity, which in turn caused greater drying shrinkage in the concrete compared to those with normal aggregates. Furthermore, the drying shrinkage at early age was more pronounced at up to 56 days for all the specimens. At a prolong drying period, the drying shrinkage observed was nearly horizontal line which shows a very low increase in the drying shrinkage probably due to the fact that the specimens at this age are mostly dried. It was observed that the drying shrinkage increased with the increase in TCA content due to the porous nature of the TCA which tend to absorb the mixing alkaline solution and also the drying shrinkage decreased over time for all specimens. Relating the drying shrinkage with porosity and water absorption it was noticed that specimens with high porosity and water absorption exhibit the highest drying shrinkage.

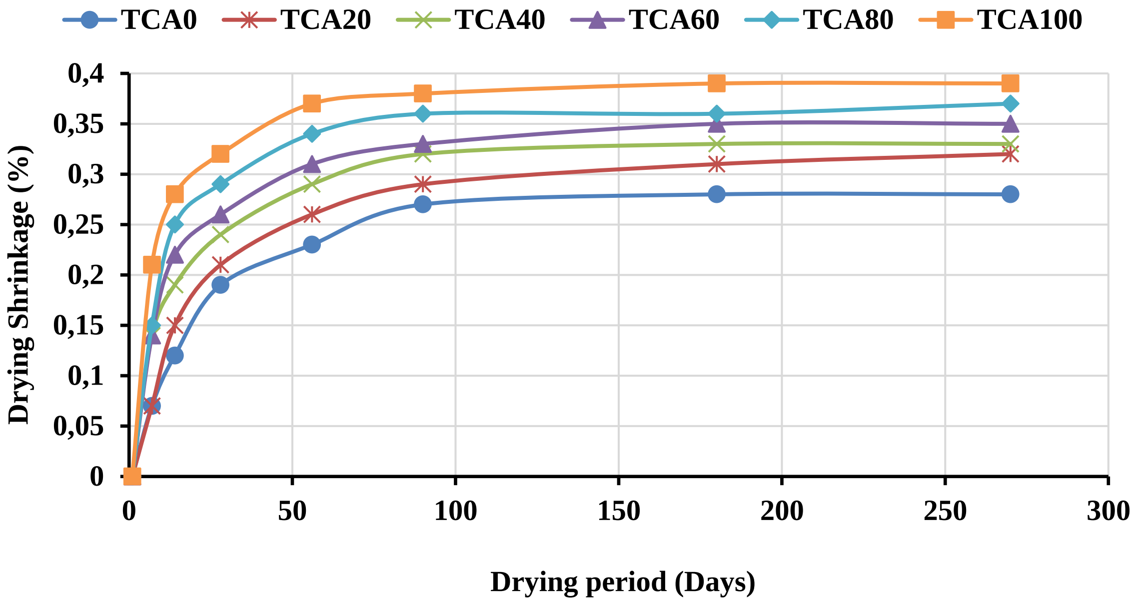

Fig. 22. Effect of TCA inclusion on drying shrinkage

3.8. Resistance to Sulphate Attack

Concrete is increasingly utilized across diverse applications and challenging environments. In such conditions, conventional concrete may not always meet the required standards of quality or durability throughout its lifespan. Sulphate attack led to ordinary concrete deterioration due to the removal of hydration products forming ettringite and gypsum which led to the expansion of the concrete and transformation of C-S-H to magnesium sulphate hydrates (M-S-H), this causes strength reduction [38]. Patil et al. [39] reported that geopolymer concretes greatly resist sulphate attack, it shows no sign [38] of compressive strength degradation, mass, length change, and physical appearance. In this study, the POFA: GGBS lightweight geopolymer concrete resistance to aggressive environment was assessed in terms of sulphate resistance. The specimens subjected to the $MgSO_4$ solution were assessed for weight loss over the immersion period of 0, 28, 56, and 180 days, respectively. Similarly, the compression strength of these specimens was determined and compared to the strength of the specimens subjected to ambient curing at 28, 56, and 180 days, respectively.

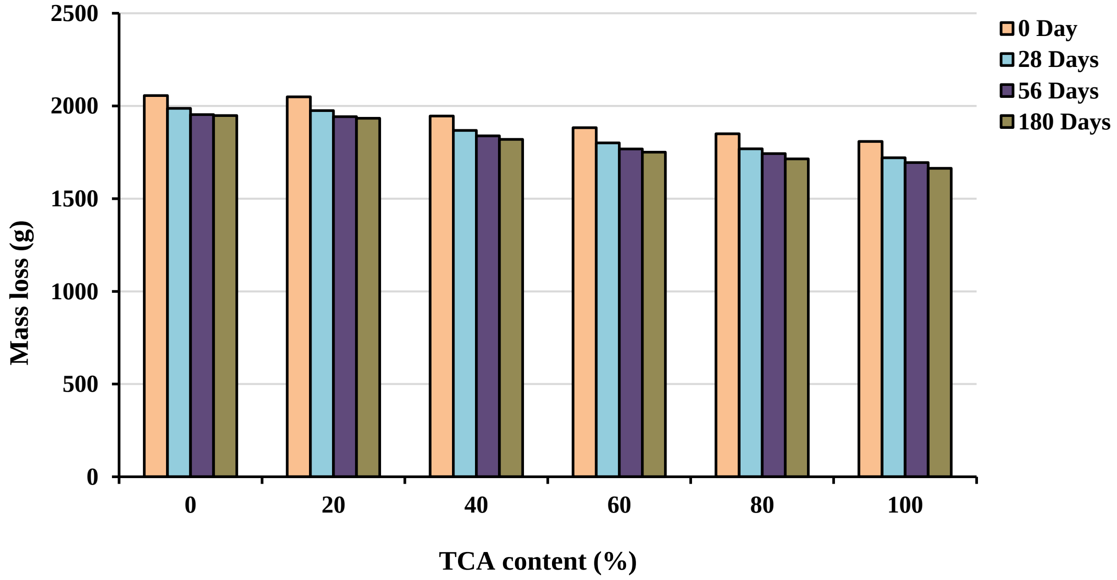

Fig. 23. Mass loss of specimens subjected to $MgSO_4$ solution up to 180 days

The visual test of the lightweight POFA: GGBS geopolymer concrete specimens subjected to $MgSO_4$ solution was carried out at 28, 56, and 180 days, respectively. It was noted that no sign of deterioration appeared on the concrete specimens at all the testing periods. This finding was also confirmed by Kabir et al. [40]. The weight reduction of all the specimens subjected to $MgSO_4$ solution with the increase in immersion period was examined and presented in Fig. 23 below. Compared to specimens' weight at 28 days, the weight loss at 180 days were 1.95, 2.09, 2.6, 2.80, 3.08, and 3.34% for 0, 20, 40, 60, 80, and 100% TCA, respectively. In general, it was observed that the mass of all the tested specimens reduced with the increase in the immersion period. Similarly, weight loss was in line with the water absorption test result, that is the highest weight loss was recorded for specimens with highest content of TCA. This was probably due to voids presence in the specimens with the high TCA content which makes it easier for the sulphate ions to penetrate the concrete compared to less void's concretes.

Table 5. Strength development and percentage reduction of concretes subjected to $MgSO_4$

TCA Content (%)	28 Days comp. strength (MPa)			56 Days comp. strength (MPa)			180 Days comp. strength (MPa)		
	Control	$MgSO_4$	% Loss	Control	$MgSO_4$	% Loss	Control	$MgSO_4$	% Loss
TCA0	52.31	51.36	1.82	53.82	51.90	3.57	56.44	54.30	3.79
TCA20	48.10	47.05	2.18	48.90	47.10	3.68	49.28	48.08	2.44
TCA40	41.63	40.82	1.95	42.88	41.28	3.73	44.21	42.79	3.21
TCA60	37.70	36.81	2.36	38.62	37.24	3.57	40.05	38.78	3.17
TCA80	34.58	33.62	2.78	34.92	34.18	2.12	37.52	36.43	2.91
TCA100	28.21	27.45	2.69	29.31	28.22	3.72	31.10	30.18	2.96

Table 5 presents the development in strength and the percentage reduction in strength of the POFA: GGBS lightweight geopolymer concretes. The impact of the $MgSO_4$ solution on the compressive strength of concrete was assessed by comparing the results of specimens exposed to the sulphate solution with those of the control specimens. At 28 days of immersion, the average strength loss was between 1.8 – 2.8% for all the specimens. However, at 180 days, the strength loss rose to 2.4 – 3.8% for all concrete specimens probably due to long term immersion. The lesser percentage of strength reduction in the geopolymer concretes was attributed to the ability of the geopolymer concretes to resist sulphate attack compared to OPC concretes.

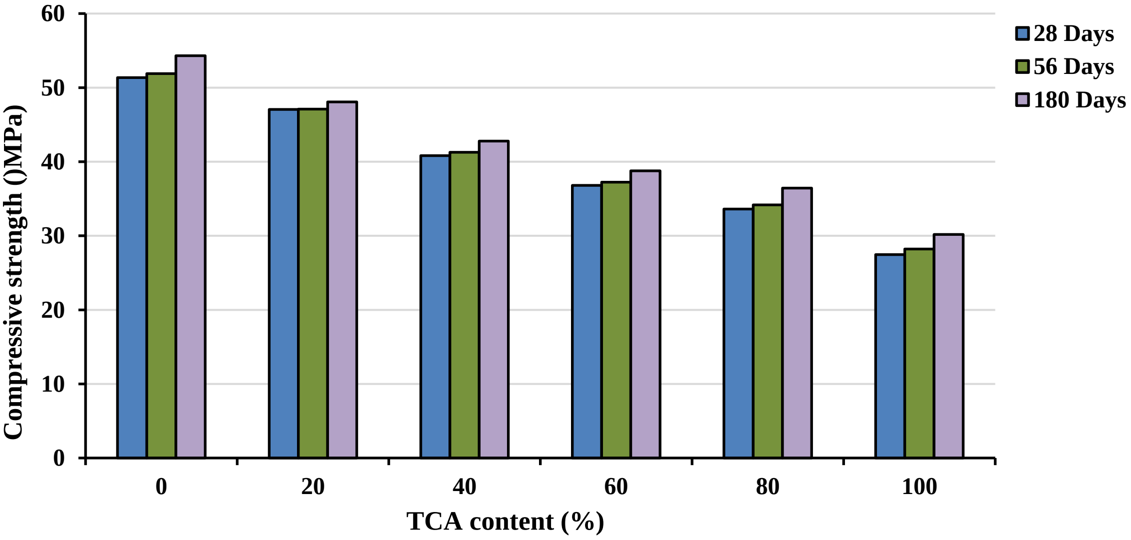

Fig. 24. Compressive strength of specimens subjected to $MgSO_4$ solution up to 180 days

As indicated in Fig. 24, the strength of the specimens before immersion in the sulphate solution was observed to increase with the duration of immersion. This strength development may be attributed to the sufficient geopolymerization over the prolong period. Similar findings were reported by other researchers where the strength of concretes subjected to sulphate solution increases with increase in the duration of immersion [41, 42].

3.9. Sustainability WA Lye Activated Lightweight Geopolymer Concrete

This study has successfully developed a friendly ambient cured geopolymer concrete activated with WA lye incorporating TCA as a promising alternative to conventional geopolymer concrete activated with NaOH. However, in order to achieve this concrete's extensive application as a sustainable construction material, it is important to investigate its environmental and economic efficiency. The environmental efficiency of concrete was conducted using the method of CO_2 Life Cycle Assessment (LCA) of concrete according to ISO 14040 [43]. LCA is an evaluation technique which takes into consideration the consequences and benefits from both upstream and downstream uses of a material across its lifetime [43].

3.9.1 Environmental Efficiency

The environmental efficiency of WA lye activated geopolymer concrete is evaluated through determining the CO_2 emission of the materials. The CO_2 factors of 0.027, 0.014, 0.041, 1.425, and 0.78 kg CO_2-eq/kg for GGBS, sand, gravel, NaOH, and Na_2SiO_3 were adopted from previous studies [44]. The given mass of 8M NaOH in 1 litre of water is 320g, this was used in the analysis due to the fact that the WA lye produced successfully compete with 8M NaOH. The CO_2 emission of POFA, WA, and TCA were ignored because they are waste materials. The embodied CO_2 index (CI) of the geopolymer concrete was calculated by dividing the 28 days compressive strength by the total CO_2 emission of the non-waste materials. The CO_2 emission of both the concretes were presented in Table 6. It was noted that the CO_2 emission of normal weight geopolymer concrete activated with 8M NaOH (NWGC) was almost 25.32% higher than that of the LWGC, this was credited to the total and partial replacement of both NaOH and natural gravel by WA lye and TCA, respectively.

Moreover, the CI of both NWGC and LWGC were determined as 0.23 and 0.23, respectively as presented in Table 7. It was observed that the eco-efficiency of both geopolymer concretes were similar, this was due to the fact that the compressive strength of the NWGC activated with NaOH is higher than that of the LWGC activated with WA lye. Sandanayake et al. [44] and Yang et al. [45] also observed similar findings, they reported that the use of geopolymer/alkali activated concretes contributes to CO_2 emission reduction in comparison to conventional concretes.

Table 6. CO_2 emission of cubic meter of NWGC and LWGC

Concrete type	28 Days comp. strength (MPa)					Total ($kgCO_2$-eq/m^3)
	GGBS	Sand	Gravels	NaOH	Na_2SiO_3	
NWGC	3.65	10.59	36.42	25.65	131.63	207.94
LWGC	3.61	6.93	14.57	-	130.18	155.29

Table 7. Embodied CO_2 index of NWGC and LWGC

Concrete type	28 days compressive strength	Total carbon emission ($kgCO_2$-eq/m^3)	Embodied CO_2 index
NWGC	48.85	207.94	0.23
LWGC	35.93	155.29	0.23

3.9.2 Cost Efficiency

In addition to environmental impact, the cost efficiency of LWGC and NWGC plays a vital role in assessing the overall sustainability of these materials, as the affordability of raw components greatly affects their feasibility for widespread use. The cost of independent constituents of the LWGC incorporating was estimated as shown in Table 8. The prices of the materials were based on the current market price in Malaysia and does not include transportation cost. The prices of the individual constituents are RM0.240, RM0.036, RM0.041, RM5 and RM58/kg, for GGBS, sand, gravel, Na_2SiO_3, and NaOH respectively. The cost of NWGC activated with 8M NaOH was also calculated for comparison purpose. The cost efficiency is determined by dividing the 28 days compressive strength by the cubic meter total cost. Similarly, all the cost of POFA, WA, and TCA were not considered because they are waste materials. Total costs of both NWGC and LWGC were RM1983.81 and RM898.93, respectively, indicating a cost reduction of about 54.69% which was attributed to the complete and partial replacement of NaOH and natural gravel, respectively. The 28 days compressive strength of both the LWGC and NWGC were 35.93 and 48.85MPa, respectively. Thus, the cost efficiency of NWGC was 0.02, while that of LWGC was 0.04. This lower cost efficiency of NWGC indicates that it is more expensive than LWGC. With a lower cost-to-strength ratio, LWGC is more cost-effective per unit of strength compared to NWGC. Although NWGC has a higher compressive strength, its higher cost makes it less efficient overall.

Table 8. Cost of cubic meter of NWGC and LWGC

Concrete type	Materials cost (RM/m^3)					Total
	GGBS	Sand	Gravels	NaOH	Na_2SiO_3	(RM/m^3)
NWGC	32.40	27.24	36.42	1044	843.75	1983.81
LWGC	32.05	17.81	14.57	-	834.50	898.93

4. Conclusions

This study investigates on the performance of WA lye activated POFA geopolymer concrete incorporating TCA as partial replacement for natural aggregates, with the aim of evaluating the mechanical properties, durability and environmental impact. The concluding remarks from the results are as follows:

- The incorporation of TCA into WA lye activated geopolymer concrete led to lower compressive, flexural, and splitting tensile strengths compared to the control specimens. This reduction in strength can be attributed to the decrease in density caused by the porous nature of TCA. The addition of TCA in the geopolymer concrete reduced its density, which in turn lowered the compressive strength.
- The integration of TCA in the WA lye activated geopolymer concrete increases the water absorption and the drying shrinkage of the concrete which were credited to the porous nature of the TCA. However, the water absorption was below the maximum limit specified by BS882: 1992.
- The durability of the TCA-incorporated geopolymer concrete was assessed by immersing specimens in $MgSO_4$ solution and comparing the strength results with control specimens. After 28 and 180 days of immersion, TCA-incorporated geopolymer concrete exhibited a relatively low strength loss, ranging between 1.8 – 2.8% at 28 days and 2.4 – 3.8% at 180 days. This demonstrates the geopolymer concrete enhanced resistance to sulfate attack compared to conventional OPC concrete, which typically experiences much higher strength loss under similar conditions. The lower strength loss in sulfate-rich environments is especially important for infrastructure exposed to harsh conditions, like sewage systems and marine structures, where OPC concrete is susceptible to early degradation.
- The incorporation of TCA in geopolymer concrete not only enhances the environmental profile but also contributes to cost-effectiveness. By utilizing TCA, it will be reduced with need for natural aggregate, make it an attractive alternative to traditional concrete for sustainable construction. Optimum replacement of TCA in geopolymer concrete can be further study to achieved an effective balance between the strength and sustainability.

In conclusion, the results of this study highlight the potential of TCA as a viable partial replacement for natural aggregates in geopolymer concrete, offering significant benefits in terms of mechanical properties, durability, and cost-efficiency. The ability of geopolymer concrete incorporating TCA to withstand sulfate attack, with its reduced environmental footprint and cost-effectiveness, offering a promising sustainable building material for the future. These findings not only expand the existing knowledge on geopolymer concrete but also encourage its wider adoption in the construction industry as an eco-friendly and durable alternative to traditional concrete.

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