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Properties of Concrete Containing Large Volumes of Ground Granulated Blast Furnace Slag and Ground Coal Bottom Ash with Lime Kiln Dust

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Abstract. Currently, there is no report on the combined use of ground coal bottom ash (GCBA) and ground granulated blast furnace slag (GGBS) as supplementary cementitious material (SCM) with lime kiln dust (LKD) as an additive in mortar. Hence, the current work aimed to investigate the impact of the addition of LKD on the properties of ternary blended cement mortar consisting of a large volume of GCBA and GGBS as SCM. The total substitution level of cement was up to 80%, where 50% of GGBS was combined with 0 to 30% of ground CBA. LKD was used with a content of 0%, 4% and 8%. A polycarboxylate-ether-based superplasticiser was used to achieve the mortar's flow diameter of 200 ± 10 mm. Also, the fine aggregate-to-binder and water-to-binder ratios were fixed at 3.0 and 0.4, respectively. The result revealed that the setting time of the mortar increased by increasing the cement replacement level by GCBA. Besides, the setting time was reduced with increased LKD content. All the mortar mixtures are considered good quality according to the ultrasonic pulse velocity (UPV) results. The UPV values decrease with the increased GCBA replacement ratio but increase with extended curing ages. The mortar incorporating up to 15% GCBA achieved comparable or greater strength than the control mortar (50% OPC and 50% GGBS) at a curing age beyond 28 days. Moreover, increased strength performance was noticed with increased LKD content from 0% to 8%.

1. Introduction

During the last century, concrete has been referred to as a liquid stone or artificial mixture material mainly used globally [1]. It has been developed as a primary building material used in infrastructure development [2]. As concrete is manufactured from available raw materials worldwide, thus, it's a low-cost material. Also, concrete is a versatile material that allows for architectural freedom [3]. The demand for cement is continuously increasing due to the rise in concrete development projects, expansion of industrialisation and urbanisation, and rapid infrastructure growth worldwide [4, 5]. Globally, there are approximately 1.5 to 3 tonnes per capita per annum for the rate of concrete production. According to Nwankwo, Bamigboye [6], global cement manufacturing has climbed from 0.94 to 2.28 billion tonnes from 1970 to 2005 and 4.05 to 4.1 billion tonnes from 2017 to 2018, with an expected 45% increase in cement production by 2050. As a result, the concrete industry, which also comprises all its suppliers, is a critical participant in the construction industry [3]. However, the massive manufacture of cement



contributes to significant carbon dioxide (CO₂) emissions and results in global warming [5]. Thus, environmental factors have been an essential topic of discussion and concern [7]. The production of 600kg of cement would emit about 400kg of CO₂ into the atmosphere [8]. Many preeminent approaches and investigations have been performed to decrease the adverse impact of cement manufacturing by applying industrial by-products such as silica fume, sugarcane bagasse ash, and fly ash as cement replacement materials [9]. This act has been shown to minimise clinker production, reduce CO₂ emissions and conserve non-renewable raw resources for cement production [5].

Besides, coal is one of the world's most essential energy sources, contributing to about 40% of global electricity generation [10]. For example, seven coal-fired power stations generate around 9000 MW of energy [11]. Two waste products developed in coal power plants are coal bottom ash (CBA) and coal fly ash (CFA). CFA refers to the lighter coal ash component that rises to the exhaust stacks, whereas CBA refers to the heavier coal ash component that falls on the bottom of the coal furnace [12]. However, due to the larger percentage of unburned carbon, different structural features and the considerable hazard to human well-being and the climate, CBA is not commonly used as a supplementary cementitious material (SCM) in concrete. Instead, CFA is commonly incorporated as an SCM in concrete due to its similar properties to cement [13].

In previous research, CBA has been used as a fine aggregate substitute in concrete due to its coarser size and physical properties. Compared to the natural aggregate, bottom ash is lighter, brittle, and resembles cement clinker. However, because of its lightweight nature and excellent water absorption, it is a viable alternative in high-strength or lightweight concrete. In the meantime, numerous studies revealed that the pulverised CBA can be categorised as class F pozzolanic material in accordance with ASTM C618-19 and can be utilised as SCM in concrete [14].

Ground granulated blast furnace slag (GGBS) is a feasible SCM option in synthesising binary and ternary blended cement. GGBS is a by-product of iron and steel manufacture formed by water-quenching molten iron slag from a blast furnace. Subsequently, the granular product was dried and pulverised into a fine powder, resulting in a glassy substance [15]. The chemical composition of slag varies greatly, relying upon the unrefined substance utilised in the iron assembling process [16]. Because of its chemical and physical qualities, GGBS offers OPC numerous advantages, including enhanced workability, durability, and compressive strength performance [17]. In addition, GGBS is a very fine glassy powder that can enhance the particle bonds, thus increasing the chloride resistance of concrete [17]. As a result, the interior reinforcement is protected against corrosion. However, the presence of high content of GGBS may result in increased carbonation depth because of the decreased calcium hydroxide (CH) formed during hydration [17].

Lime kiln dust (LKD) is a by-product of high-temperature rotary kilns used in lime production. It can be obtained through air pollution control technologies such as bag houses, electrostatic precipitators and cyclones [18]. The chemical compositions of LKD by-products may vary depending on the plants since they are impacted by the type of limestones used, the kiln, the fuel utilised and the kiln operation conditions [19]. LKD have a comparatively high proportion of CaO [19]. Over 2.5 to 3.6 million metric tonnes of LKD have been produced annually in the United States and approximately 1.5 tonnes per day for a single factory in Malaysia [20].

There were numerous studies on the utilization of coal bottom ash as replacement material for fine aggregate and also cement in binary blended cement system. Nevertheless, far too little attention has been paid to utilising both GGBS and GCBA in ternary blended cement system. Meanwhile, there is no exploration on the use of LKD as an additive in concrete. Due to its inherent alkaline properties of LKD, there is a need to concentrate on developing LKD as an additive for blended cement composites. Hence, it has a high potential for supplementing the alkali solution needed for the early age secondary hydration of the amorphous aluminosilicates of GGBS and GCBA. Therefore, this investigation aims to determine

the influence of use of LKD as an additive on the properties of mortar containing a large volume of GCBA and GGBS as the SCM.

2. Experimental Programme

2.1. Materials

This research uses materials containing OPC, GGBS, GCBA, and LKD as an additive, quarry dust as a fine aggregate, and water and T-PEG as a PCE chemical admixture. The material properties and details will be explained as follows.

2.1.1. Ordinary Portland Cement (OPC). Portland cement is manufactured as a fine powder by heating and grinding a combination of raw materials like limestone and clay. According to ASTM C150/C150M-20 [21], five types of Portland cement are available and standardised. Type I cement, ordinary Portland cement (OPC) with specific gravity (SG) of 3.15, is incorporated in this research as shown in Figure 1. The fineness of the OPC was 3736 cm²/g. The OPC was obtained from a local supplier (Panda Blue brands) and complied with MS EN 197-1:2014 CEM I 52.5N standards [22]. The chemical composition of OPC [23] is shown in Table 1. Compounds such as lime, alumina, silica and iron oxide are the principles of cement production [24]. These oxides will combine in the kiln to generate more complex compounds at high temperatures. The proportional proportion of these oxide compositions influences cement features, the fineness of pulverisation, and the rate of cooling [24].



Figure 1. Ordinary Portland cement (OPC).

2.1.2. Ground Granulated Blast Furnace Slag (GGBS). GGBS is a by-product that has become popular as a concrete replacement material. Numerous studies and research also demonstrated that incorporating GGBS in concrete does not reduce the concrete's strength [25, 26]. The chemical compositions of GGBS [23] typically consist of four main compounds, as shown in Table 1. The SG of GGBS is 2.93 and the properties of GGBS comply with the specifications described in MS EN 15167-1:2010 [27]. The fineness of GGBS was 4598 cm²/g and Figure 2 demonstrates the GGBS used in this study.



Figure 2. Ground granulated blast furnace slag (GGBS).

2.1.3. Ground coal bottom ash (GCBA). In this research, the dried CBA was ground in a ball mill for five hours to ensure more than 95% of ground CBA (GCBA) passing the 75 μm test sieve. The fineness and SG of GCBA were 3902 cm^2/g and 2.76, respectively. Figure 3 demonstrates the GCBA used in this research work. According to Table 1 [23], the total SiO_2 , Fe_2O_3 and Al_2O_3 content was more than 70% and the content of SO_3 was less than 5%. Hence, the GCBA can be categorized as class F pozzolanic material according to ASTM C618-19 [28].



Figure 3. Ground coal bottom ash (GCBA).

2.1.4. Lime kiln dust. The SG and fineness of the LKD were 2.79 and 5241 cm^2/g , respectively [29]. Figure 4 shows the LKD used in this study. The chemical composition of the LKD is shown in Table 1. It was observed that the LKD consists of high content of CaO (66.91%) with minor content of SiO_2 (0.12%) and MgO (0.34%).



Figure 4. Lime kiln dust (LKD).

2.1.5. Fine Aggregate. Quarry dust, a by-product of rock-crushing projects, is used as fine aggregate in the fabrication of mortar specimens. Figure 5 demonstrates the quarry dust used in this research work. In this research, the quarry dust is cleaned and sieved through a 5mm BS 410 test sieve to remove coarser aggregate and organic residues. The SG of quarry dust is 2.64 [30], and the chemical composition is indicated in Table 1.



Figure 5. Quarry dust.

Table 1. Chemical composition of supplementary cementitious materials and quarry dust [23, 29, 30].

Chemical composition	Percentage content (%)				
	OPC	GGBS	GCBA	LKD	Quarry dust
CaO	59.1	43.1	5.9	66.91	9.9
SiO ₂	22.0	34.2	53.5	0.12	60.1
Al ₂ O ₃	9.5	11.4	21.2	0.05	16.1
Fe ₂ O ₃	2.9	0.5	9.3	0.04	8.3
TiO ₂	0.1	0.7	0.9	0.01	-
MnO	0.1	0.7	0.1	-	-
MgO	-	5.6	2.3	0.34	5.4
SO ₃	4.9	2.5	0.1	-	0.1
K ₂ O	0.5	0.8	1.4	0.01	0.02

2.1.6. Superplasticizer. The conventional admixture provides high early strength of concrete. However, the high workability loss over time would reduce the final strength of concrete. Hence, the polycarboxylate ether (PCE) superplasticiser was used to enhance the slump retention and the final strength of the mortar. This research used a PCE superplasticiser to achieve the target mortar flow of 200 ± 10 mm at a fixed water-to-binder ratio.

2.2. Mix Design and Proportioning

Table 2 indicated that LKD was used as an additive at 0%, 4% and 8%. The mix design and proportioning of the mortar were designed according to the standard procedures prescribed in ACI 211.1 using the absolute volumetric method [31]. The GGBS's content remained at a 50% replacement level, while GCBA substituted the OPC at a 15% and 30% replacement level. Therefore, the OPC-GGBS blended mortar containing an equal amount of GGBS and OPC with 0 to 8% of LKD as an additive (L0OPC50, L4OPC50 and L8OPC50) was indicated as a control mix. Besides, the fine aggregate-to-binder ratio (A/B) and water-to-binder ratio (W/B) remained constant at 3.0 and 0.4, respectively.

Table 2. Mix proportion of GGBS-GCBA cement blended mortar containing LKD as an additive.

Mix Code	Mix Proportion										
	OPC	GGBS	GCBA	LKD		Quarry Dust	Water	W/B ratio	A/B ratio	SP	Flow
	(kg/m³)	(kg/m³)	(kg/m³)	(%)	(kg/m³)	(kg/m³)	(kg/m³)			(%)	(mm)
L0OPC50	268	268	0.00	0	0.00	1608	214	0.4	3.0	0.7	210
L0OPC35GCBA15	187	266	80	0	0.00	1599	213	0.4	3.0	0.7	210
L0OPC20GCBA30	106	265	159	0	0.00	1589	212	0.4	3.0	0.7	200
L4OPC50	268	268	0.00	4	20	1588	214	0.4	3.0	0.9	210
L4OPC35GCBA15	187	266	80	4	20	1578	213	0.4	3.0	0.6	210
L4OPC20GCBA30	106	265	159	4	20	1569	212	0.4	3.0	0.6	200
L8OPC50	268	268	0.00	8	41	1567	214	0.4	3.0	0.7	210
L8OPC35GCBA15	187	266	80	8	40	1558	213	0.4	3.0	0.7	200
L8OPC20GCBA30	106	265	159	8	40	1549	212	0.4	3.0	0.7	210

3. Method of preparation and test

The materials such as GGBS, OPC, GCBA and quarry dust were prepared according to the mix proportions stated in Table 2 and poured into the mixer. Firstly, the materials were mixed in dry conditions for 10 minutes to acquire a homogeneous mixture. Subsequently, 80% of the water was introduced to the mixture for further mixing of 2 minutes. Next, 20% of the water was added to the mixture and continued mixing for 2 minutes. Next, the weighted LKD was introduced to the mixture and mixed for 1 minute. Finally, the T-PEG-based chemical admixture was added to obtain the desired flow diameter of 200 ± 10 mm. A flow table or workability test assessed the flow diameter of the mortar. Subsequently, the fresh mortar was placed into the mould in 3 layers, each layer vibrated for 10 seconds using a vibrating table to eliminate the air voids. The mortar specimen was removed from the mould after 24 hours and subjected to moist curing for 7, 14, 28, 56 and 91 days.

3.1. Fresh properties

3.1.1. Setting time. Setting time test was carried out on the 150 mm x 150 mm x 150 mm mortar cube according to ASTM C403M-16 [32]. The penetrometer was used in the setting time test. The penetration needles are required to be attached to the proctor penetrometer's loading apparatus with the bearing areas 645 mm², 323 mm², 161 mm², 65 mm², 32 mm², and 16 mm². The fresh mortar mixture was placed indoors at 20 to 25°C. The initial setting time was when the penetration resistance had reached 3.5 MPa, and the mortar mixture began to harden and lose its plasticity. Also, the final setting time was when the penetration resistance reached 27.6 MPa, and the mortar had lost its plasticity and hardened. The time and the data of plunger readings were recorded.

3.1.2. Workability or Flow table. In this research, the workability of the mortar was assessed by flow table test according to procedure prescribed in ASTM C1437-20 [33]. First, the fresh mortar mixture was filled into the flow mould in 2 layers, with each layer tamped 20 times. Next, the mould was then removed instantly by pulling steadily upward. Next, the flow table was dropped 25 times within 15 seconds. Finally, the diameter of the mortar spread was measured and recorded.

3.2. Engineering properties

3.2.1 Flexural and Compressive strength. In this research, the 40 mm x 40 mm x 160 mm mortar specimen was used for the flexural strength test in compliance with ASTM C348-21 [34]. The mortar specimens were tested at the pre-determined testing ages. This test aimed to determine the specimens' ability to resist bending failure. After the flexural strength test was completed, the half-broken prism specimens were used for the compressive strength based on the standard ASTM C349-18 [35] to determine the ability of specimens to withstand the load under compression without cracking and deflection. An average value was obtained from the maximum loads of the six specimens.

3.2.2 Ultrasonic pulse velocity (UPV). The ultrasonic Pulse Velocity (UPV) test was carried out in compliance with standard BS EN 12504-4:2013 [36]. This test used two mortar cubes with dimensions 100 mm x 100 mm x 100 mm at the pre-determined curing age. The UPV test examined the quality of the specimen (the presence of internal voids and cracks) by transmitting electronic waves through the specimen. The direct transmission approach was used because it is preferable and more dependable than the other two ways in transit time and path length measurement. In addition, this method was used when testing the opposite face of the mortar specimen.

4. Results and discussion

4.1. Fresh Properties

4.1.1. Setting time. The results of setting time with the influence of GCBA as cement replacement and LKD as an additive were demonstrated in Table 3. Experimentally, the initial and final setting time increased with higher cement replacement with GCBA [37]. It is because the amount of tri-calcium silicate (C₃S) was reduced in cement paste, so it takes more time for initial and final setting time [4, 13]. It implies that the higher percentage level of GCBA replacement slowed the cement hydration process. The longer setting time was caused by the phosphate (P₂O₅) in GCBA, which slows down the cement paste by causing a complex to form on the cement particles' surface [38]. According to a study Khan [37], the cement reaction will influence the mortar's initial and final setting time. If GCBA replaces the cement, the reaction of cement available reduces, resulting in a longer initial and final setting time. They also proved that the difference between adding OBA and GBA in both circumstances was not significant. The results are practically identical.

The addition of LKD showed the setting times reduced from 0% to 8%. It can be explained that the lime content increased with the LKD content. More water was needed as the LKD content increased. Once LKD reacted with water, the accelerated hydration process reduced the setting time. These findings are congruent with the study of Latif, Naganathan [19]. They also indicated that the porous and larger particle size of LKD absorbs more water than OPC.

4.1.2. Workability or Flow table. The workability of fresh mortar is a multifaceted issue that covers a wide range of requirements in terms of mobility, stability and compatibility [39, 40]. Therefore, the W/B ratio was kept at 0.4 in all specimens. Table 3 shows the findings of the workability of the mortar mix with or without GCBA and the dosage of chemical admixture required to achieve the target flow diameter (200 ± 10 mm) in all samples.

From the findings and observations, the results of all samples were comparable, ranging between 0.60% to 0.70%. It was observed that the L4OPC50 required a slightly higher dosage of chemical admixture (0.90%) to obtain the targeted flow diameter. This was due to there was higher loss of workability during the mixing process of L4OPC50, therefore, a relatively higher superplasticizer content is required to maintain the flow diameter. The previous research from Chee Ban, Leng Ee [29] shows that increase in LKD content will increase the amount of water required to obtain the targeted flow diameter. However, the results in Table 3 demonstrated that there is no significant increase in TPEG content when the LKD content increased from 0% to 8%. It was reported that grinding of CBA will reduce the porosity of CBA particles as well as the corresponding particles' sorptivity [23, 41, 42]. Thus, the reduced sorptivity of the CBA particles able to compensate the increased water consumption as the LKD content increased from 0% to 8%. Furthermore, all the samples achieved the targeted flow diameter due to the addition of chemical admixture in this research improves the particle dispersion and thus further increases the mix's flowability [43].

Table 3. Setting time and workability results.

Mix Code	Elapsed time (hours)		TPEG Content (%)	Flow Diameter (mm)
	Initial	Final		
L0OPC50	2.83	4.58	0.70	210
L0OPC35GCBA15	3.20	5.75	0.70	210
L0OPC20GCBA30	3.95	7.15	0.70	210
L4OPC50	2.87	4.67	0.90	210
L4OPC35GCBA15	3.00	4.75	0.60	200
L4OPC20GCBA30	3.50	6.83	0.60	200
L8OPC50	2.55	4.50	0.70	210
L8OPC35GCBA15	2.60	4.58	0.70	210
L8OPC20GCBA30	3.17	6.17	0.70	210

4.2. Engineering Properties

4.2.1. Compressive Strength. Figure 6 demonstrated that the mortar's compressive strength reduced with increasing content of GCBA but increased with prolonged ages. The lower compressive strength of mortar consisting of higher content of GCBA was due to increasing cement replacement by GCBA led to less calcium hydroxide (CH) for the pozzolanic reaction, resulting in reduced compressive strength [41]. The increased compressive strength with curing age was contributed by the continued hydration and filling of pores with calcium silicate hydrates (C-S-H) gel contributed from the pozzolanic activity of GCBA and the continuing hydration of OPC [44]. The higher cement substitution level of GCBA results in lower compressive strength. All the 7 and 14 days-strength of mortar containing 15% and 30% GCBA was lower than the control mix. This observation is attributed to the pozzolanic reaction provided by GCBA to create C-S-H in the matrix has not yet begun at the early curing ages [8, 9]. Also, the higher cement replacement by GCBA resulted in a reduced rate of hydration. Therefore, the primary C-S-H from cement hydration could not offer adequate strength as in the control specimen [5]. However, at 56 and 91 days, all the mortar incorporating 15% of GCBA had similar or greater strength than the control mortar. Incorporating GCBA improves the amount of silicate in the mortar mixture, resulting in better development of C-S-H gel and thus increasing the compressive strength [45].

In contrast, the compressive strength of mortar containing 30% GCBA at 7 days was lower than the control mix. A remarkable reduction was noticed in the strength of the mortar mixture with 30% GCBA. The diluting effect from the considerable decrease in cement content due to increased CBA replacement level was more predominant. As a result, less C-S-H and calcium hydroxide (CH) were formed from the hydration of OPC, reducing the potential pozzolanic reaction of the CBA and eventually leading to a strength reduction [46]. The hydration reaction of the cement was affected. Hence, the CBA-mortar mixture required a longer curing time to obtain comparable strength with control mixes.

According to Lo, Lee [47], calcium-silicate hydrates and calcium hydroxide/portlandite (CH/P) are the primary cement hydration compounds. C-S-H is the major contributor among these compounds in terms of compressive strength. The ash materials' pozzolanic reactions initiate after the cement hydration process. Therefore, the GCBA will be activated by CH and start to react with C-H/P to generate more C-S-H gel at later testing age. As the mortar's pores were filled with C-S-H gel from the pozzolanic reaction, the compressive strength of the mortar increased over time.

Besides, all the control mixes demonstrated the highest compressive strength among the mortar mixture. From the previous studies by Mangi, Ibrahim [12] and Mangi, Ibrahim [8], the concrete with 10% OPC replacement by GCBA achieved optimum compressive strength performance. On the other hand, this research established experimentally that 15% to 30% OPC replacement by GCBA led to the reduced compressive strength of mortar. However, the mortar consisting 15% GCBA achieved comparable strength with the control mortar (with 50% OPC and 50% GGBS) at a curing age beyond 28 days. Additionally, the control mix can minimise the content of OPC by 267.99 kg/m³, which positively impacts concrete due to heat reduction, cheaper concrete cost, and low drying shrinkage [48].

After that, it was noticed that higher LKD content in mortar resulted in greater compressive strength. The strength of the mortar mixture with or without GCBA increased as the LKD increased from 0% to 8% at 7 days. At a later curing age, a comparison trend may be detected. As mentioned before, this may be the interaction between LKD and GCBA, which led to increased compressive strength [49].

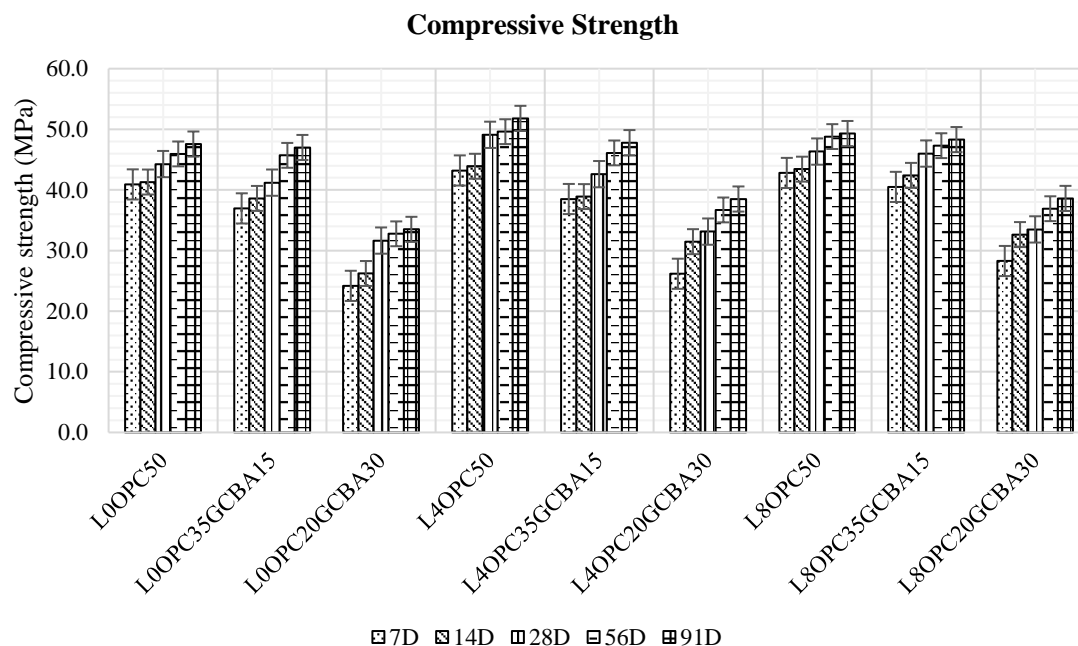


Figure 6. Average compressive strength of different mortar mixtures at 7, 14, 28, 56 and 91 days.

4.2.2. Flexural Strength. The average flexural strength of different mortar mixtures at 7, 14, 28, 56 and 91 days were depicted in Figure 7. The trend of flexural strength was similar to compressive strength. As the substitution level of GCBA increased, the flexural strength value decreased. The porous structure of the bottom ash increased the water absorption rate, hence reducing the hydration of cement particles. As a result, the paste available for bonding was decreased and bond strength between aggregate and paste was reduced [50]. This observation indicates the micro-cracks were more potential to propagate and for the interface to shatter when subjected to stress. As a result, the flexural strength decreased. According to Abdulmatin, Tangchirapat [41], the higher GCBA replacement level in concrete leads to a slower pozzolanic reaction. Then, the reduction in calcium hydroxide (CH) content results in lower flexural strength. Yet, the previous studies by Kurama and Kaya [51] showed that 10% of GCBA was the optimum cement substitution level to enhance flexural strength. Therefore, the flexural strength will be reduced if the contents of the bottom ash exceed 10% of the cement replacement level. This finding corresponds with the present study. In this research, the content of GCBA was 15% and 30%, which are over the optimum content replacement level and resulting in reduced flexural strength.

At 7 days, the flexural strength of all mortar mixtures ranged between 5.3 to 8.3 MPa. All the control mixes showed higher flexural strength than the mortar mixture containing GCBA. L4OPC50 recorded the highest flexural strength, while L0OPC20GCBA30 indicated the lowest flexural strength among all the mortar specimens. L4OPC50 implied the highest flexural strength also might be due to the high workability, as shown in Table 3. The higher workability of mortar lead to better compaction and a more homogeneous mix. This improved compaction results in fewer voids within the mortar and better flexural strength of mortar [43]. Flexural strength increased as the curing ages increased. It was due to OPC's continued hydration and pores' filling with C-S-H gel from the bottom ash's pozzolanic activity [44].

A similar tendency can be observed at later ages. The mortar specimens' flexural strength was in the order of L4OPC50 > L8OPC50 > L0OPC50 > L8OPC35GCBA15 > L4OPC35GCBA15 > L0OPC35GCBA15 > L8OPC20GCBA30 > L4OPC20GCBA30 > L0OPC20GCBA30. However, for 0% and 8% LKD, the 15% GCBA mortar mixture at 28 days indicated comparable strength with the 0%

GCBA mortar mixture at 7 days. Only the mortar mixture with 30% GCBA had lower flexural strength than the control mix at all ages. As the LKD content increased, the flexural strength also increased. It could be due to the interaction between LKD and GCBA, as discussed earlier [49].

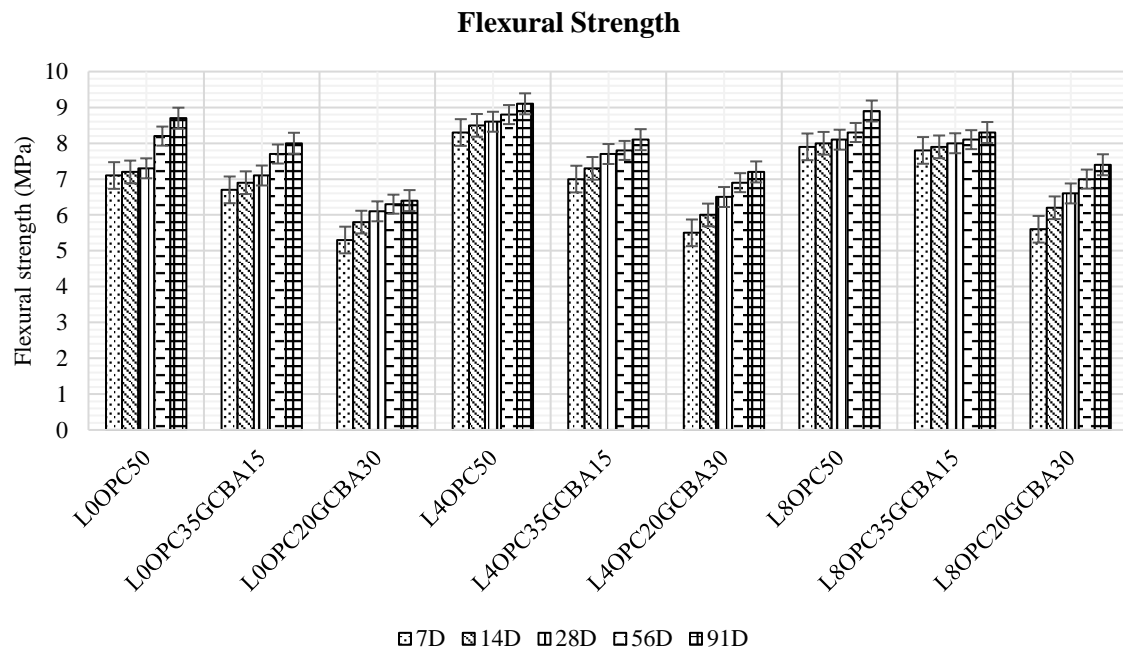


Figure 7. Average flexural strength of different mortar mixtures at 7, 14, 28, 56 and 91 days.

4.2.3. Ultrasonic pulse velocity (UPV). Figure 8 depicts the UPV findings of mortar specimens at the pre-determined curing ages. The grading of mortar quality according to the UPV values is shown in Table 4 [52-54]. All the mortar specimens were considered good quality at all curing ages, with UPV values ranging from 3500m/s to 4500m/s.

At 7 days, the UPV values of all ternary blended mortar mixtures were lower than the control mortar mix. The UPV values of the L0OPC35GCBA15, L0OPC20GCBA30, L4OPC35GCBA15, L4OPC20GCBA30, L8OPC35GCBA15, L8OPC20GCBA30 were lower by 2.31%, 5.46%, 2.89%, 5.90%, 2.30% and 5.08% respectively when compared to the control mix (L0OPC50, L4OPC50 and L8OPC50). After 28 days, the UPV values of L0OPC20GCBA30, L4OPC20GCBA30 and L8OPC20GCBA30 were lower than the control mix, except for L4OPC35GCBA15. In mixtures L0OPC35GCBA15 and L8OPC35GCBA15, it can be noticed that UPV values decrease with the increased GCBA replacement ratio but increase with prolonged curing ages. These results were similar to the study by Baite, Messan [55] and Singh and Siddique [56]. In all concerned curing ages, they revealed that increasing the CBA substitution ratio decreased the UPV values of CBA mortar. The UPV values of the L0OPC35GCBA15 and L8OPC35GCBA15 at 28 days were comparable to the control mix, L0OPC50 and L8OPC50 at 7 days. Ong, Mo [11] also discovered a little variation in UPV values between traditional concrete and CBA concrete. Besides, all the specimens showed increased UPV values at a later curing age due to C-S-H production caused by cement hydration and decreased voids in the mortar [43]. The higher values of UPV obtained in this research also demonstrate that bottom ash mortar mixes' density, uniformity and homogeneity were satisfactory [57].

As the LKD content increased, the UPV values increased. The results are congruent with the compressive and flexural strength results. LKD may explain that increased calcium oxide (CaO) in LKD from 0% to 8% will increase UPV values. According to Chindaprasirt, Phoo-ngernkham [49], the free

calcium ions and calcium hydroxide in LKD interacted with silica and alumina in the bottom, ash-producing more C-S-H and calcium aluminate silicate hydrates (C-A-S-H) within the matrix. The products of the reaction between calcium and water moved faster because of the heat made by the exothermic reaction. Because there was C-S-H, C-A-S-H and heat, the material quickly hardened and was very strong [49].

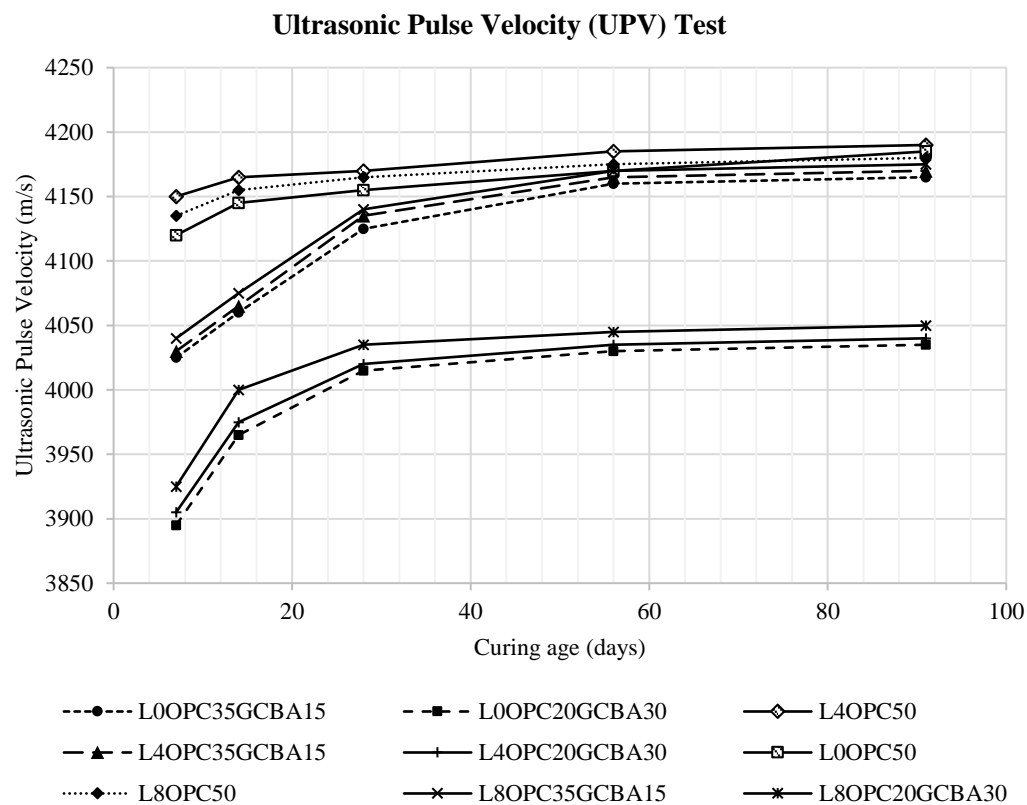


Figure 8. UPV test results for different mortar mixtures.

Table 4. Classification of concrete quality according to the UPV value [52-54].

UPV (m/s)	Concrete Quality (Grading)
≥ 4500	Excellent
3500 – 4500	Good
3000 – 3500	Questionable
2000 – 3000	Poor
≤ 2000	Very Poor

5. Conclusions

Several conclusions were derived based on the experimental tests and analysis of the fresh and engineering properties of mortar performed in this study. The ternary blended cement with a constant value of GGBS and various replacement levels of GCBA and OPC, as well as different contents of LKD as an additive, are stated as follows.

- The workability results show that the chemical dosage required for the mortar mixture to attain workability of 200 ± 10 mm ranged from 0.60% to 0.90%.
- All the mortar mixtures are considered as good quality at all curing ages, with UPV values ranging from 3500 ms^{-1} to 4500 ms^{-1} .

- The UPV values decrease with the increased GCBA replacement level but increase with extended curing periods because the production of C-S-H reduced voids in the mortar.
- The increased GCBA's cement replacement level from 0% to 30% led to reduced compressive and flexural strength due to the cement dilution effect. However, the strength performance of the mortar increased in prolonged curing ages because the continuous pozzolanic reaction led to the formation of C-S-H gel.
- The setting time of the mortar was reduced with increased LKD content. In addition, when the LKD reacts with water, the hydration reaction increases, thus leading to reduced setting time.
- As the LKD content increased from 0% to 8%, the UPV values increased due to the increased calcium oxide (CaO) content in the mortar mixture. In addition, the reaction between the free calcium ions and calcium hydroxide in LKD with the silica and alumina in the bottom ash resulted in extra C-S-H and C-A-S-H within the cement matrix.
- As the LKD content increases, the compressive and flexural strength of the mortar could be due to the interaction between LKD and GCBA, thus enhancing the strength performance of the mortar.

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