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Drying Shrinkage Properties and Engineering Performance for Cement Mortar Containing Bamboo Biochar Powder (BCP)

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ABSTRACT

Drying shrinkage, the reduction in volume as a material like cement mortar dries, can result in cracks and decreased durability. Bamboo biochar powder (BCP) serves as a substitute for cement in mortar, affecting its drying shrinkage characteristics. Research has shown that BCP in cement mortar can alleviate drying shrinkage by absorbing and retaining moisture. This study aims to assess the chemical and physical properties of BCP, determine the mechanical attributes of bamboo biochar mortar with varying percentages of cement replacement, and investigate the impact of BCP on mortar shrinkage in indoor and outdoor tropical conditions. BCP, derived from Gigantocholoa Abociliata species and sized at 75 µm, was used to replace cement rates of 0%, 5%, 10%, 15%, and 20%. Sixty cube samples (50x50x50mm) were employed for density, ultrasonic pulse velocity (upv), compressive strength, and water absorption tests. Additionally, thirty prism samples (100x100x400mm) were employed to assess drying shrinkage during outdoor and indoor exposure, spanning up to 150 days. The experimental data indicates a consistent trend as the percentage of cement replacement increases in the mortar mix, density, and compressive strength decrease, while UPV and water absorption increase. The lowest shrinkage strain was observed during indoor exposure with 5% cement replacement, attributed to BCP acting as a filler, creating strong bonding properties, and reducing shrinkage. Conversely, the highest strain was noted during outdoor exposure with 20% cement replacement, resulting from higher moisture loss. In summary, a 5% replacement of cement with BCP in mortar offers the most effective reduction in shrinkage strain.

Keywords: *Shrinkage, Engineering Performance, Cement Mortar, Bamboo Biochar Powder*

1. INTRODUCTION

The construction industry is one of the major contributors to CO_2 emissions globally due to the energy-intensive processes involved in cement production for concrete and mortar [1]. Addressing these issues, this study explores the use of bamboo biochar powder (BCP) as a sustainable alternative to traditional materials. Biochar is known for its efficient CO_2 adsorption and high affinity for non-polar chemicals due to its porous surface, offering potential benefits for carbon sequestration in cementitious materials [2].

Traditional cement mortar designs often suffer from insufficient water content, leading to poor workability and increased brittleness, which subsequently causes surface cracking [3]. Incorporating BCP in cement mortar aims to mitigate these issues by enhancing the material's properties and reducing surface cracking. Moreover, the utilisation of bamboo biochar supports the reduction of agricultural waste, typically disposed of through open burning, thereby minimising environmental pollution [4]. BCP is proposed as an alternative to silica fumes in cementitious composites, promoting waste recycling and potentially decreasing the land required for waste disposal [5].

The fine particle size of BCP (75 microns) can effectively fill voids within the cement mortar, increasing its density [6]. Additionally, BCP partially replaces cement in the mixture, addressing the hydration challenges associated with Portland cement, which requires substantial water to sustain hydration, particularly at later stages. The fine particles of BCP exhibit high water adsorption properties, acting as an internal curing agent within the cement paste [7]. This internal curing capability suggests the material's viability for civil engineering applications, where improved mechanical properties such as compressive strength are desired. However, the proportion of BCP used must be carefully controlled to avoid adverse effects on the mortar [8].

Bamboo biochar, derived from bamboo waste through slow pyrolysis, is a renewable material due to bamboo's rapid growth cycle. Its high availability, porous structure, and large surface area have long established its functionality [9-

10]. The slow pyrolysis process involves heating bamboo waste to approximately 500°C in an oxygen-free environment, typically at a rate of 10°C/min, until it is fully carbonised [11].

In this study, we focus on the drying shrinkage properties of cement mortar incorporating BCP. Drying shrinkage is the reduction in volume as the material dries, which can lead to cracks and reduced durability in cement mortar. BCP's ability to absorb and retain moisture, owing to its porous structure, helps mitigate drying shrinkage [12]. Through experimental testing, the optimal dosage and dispersion of BCP were identified, highlighting its potential to improve mortar properties and reduce environmental impact from CO_2 emissions associated with cement production. This study aims to evaluate the chemical and physical properties of BCP, determine the mechanical properties of bamboo biochar mortar in its hardened state with varying percentages of cement replacement, and investigate the effect of BCP on mortar shrinkage under tropical indoor and outdoor conditions.

2. MATERIALS AND METHODS

2.1. Cement and Sand Used

Ordinary Portland Cement (OPC) from Tasek Corporation Berhad, was used as the binding agent in the mixture of mortar cubes and beams. The mixture of mortar requires the inclusion of inert material as a filler to reduce the probability of the specimen shrinking, hence, fine aggregate was used as the filler material in this study. A particle size distribution chart was obtained from sieve analysis results. Five different sieve sizes were used, 5mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, and pan (0.15mm). Sieve analysis was conducted according to ASTM C136 / C136M-14 [23], and the results for particle size distribution are shown in Fig. 1. When referred to the standard code ASTM C136/C136M-14, the lower limit for sieve size 5.00mm was 89%, sieve size 2.36mm was 60%, sieve size 1.18mm was 30%, sieve size 0.60mm was 15%, and sieve size 0.30mm was 5%. The fine aggregate for this study was subjected to a sieve analysis to determine its suitability for use in mortar mixtures. The aggregate passed through various sieve sizes with the following retention percentages: 100% for the 5.00mm sieve, 94% for the 2.36mm sieve, 65% for the 1.18mm sieve, 34% for the 0.60mm sieve, and 13% for the 0.30mm sieve. Based on these retention percentages, the sand was appropriate for use as a raw material in the mortar mixtures.

2.2. Preparation and Processing of Biochar

Bamboo biochar (BC) was used as the raw material in this study. It was obtained from Tadom Hill Resorts, Selangor, Malaysia. This solid waste was collected from various species of bamboo waste. It is typically produced from the culms or refuse of mature bamboo plants and burned in the oven at temperatures ranging from only 200 to 600°C. Bamboo biochar (BC) was used as the raw material in this study. It was obtained from Tadom Hill Resorts, Selangor, Malaysia. This solid waste was collected in bulky size of rocks, from the various species of bamboo wastes. It is typically produced from the culms or refuse of mature bamboo plants and burned in the oven at temperatures ranging from only 200 to 600°C. Then was ground into smaller particles and sieved to pass 75 μm, known as bamboo biochar powder (BCP). BCP used in this study was in fine size, 75 microns, which could fill the void to make the cement mortar dense [14]. Percentage replacement of BCP in cement mortar was 0%, 5%, 10%, 15%, and 20% [15]. The end-products of bamboo charcoal in granular sizes. Then ground into powder sizes using Laboratory Ball Mills for 6-7 hours. The powder was then sieved through a 75 μm screen to filter the coarser particles. BCP that passed the 75 μm screen appeared more in blackish grey colour, compared to the bamboo biochar (BC) in granular size, Fig. 2 – Fig. 5.

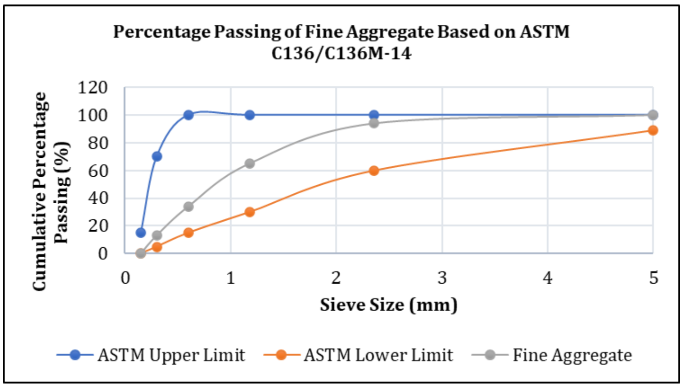

Figure 1. Particle size distribution of fine aggregate

2.3. Analysis of BCP Chemical Composition

The chemical composition analysis of Bamboo Biochar Powder (BCP) was conducted using X-ray Fluorescence (XRF) with a Phywe XR 4.0 X-Ray instrument. The process began with the preparation of a 10-gram BCP sample, which was collected post-grinding and sieving. This sample was then securely sealed in a plastic bag to maintain its integrity and sent to the laboratory for testing. In the laboratory, the XRF instrument was first calibrated to ensure accurate measurements. The BCP sample was carefully placed in the instrument, where it was exposed to X-rays. These X-rays caused the elements in the sample to emit fluorescent X-rays, which were then detected by the instrument. This detection process allowed for the identification and quantification of the various chemical elements present in the BCP. The data obtained from this analysis were meticulously recorded for further interpretation and analysis. Following the completion of the test, the BCP sample was disposed of following appropriate safety and environmental guidelines. This methodical approach ensured that the chemical composition of the BCP was analysed accurately and effectively, providing essential data for the research.

2.4. Mix Design and Casting Process

The mix proportions investigated in this research for sixty cube mortars and thirty prism mortars are presented in Table 1 and Table 2. A control mix, mortar bamboo biochar powder (MBCP0) was prepared with no cement replacement in the mixture. There were four types of percentage cement replacements, MBCP0 (0%), MBCP5 (5%), MBCP10 (10%), MBCP15 (15%), and MBCP20 (20%). Compressive strength test, density, ultrasonic pulse velocity test (upv), and water absorption test were conducted in this study. The key objectives of this research are to investigate how the addition of biochar could affect density, upv, compressive strength, water absorption, and shrinkage strain. The total number of cube specimens (50mm x 50mm x 50mm) where sixty samples have been cast in the concrete laboratory, Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh, Malaysia. The reference code for Ordinary Portland cement used in the preparation of mortar samples was ASTM C150-7 [16], for hydraulic cement mortar flow was ASTM C1437-07 [17], for compressive strength test of hydraulic cement mortars (50-mm) cube specimens was ASTM C109/C [18], for water absorption test was ASTM C1403-13 [19] and for ultrasonic pulse velocity was BS EN 12504-4:2021 [20].

Figure 2. The **s**low pyrolysis process of bamboo waste to produce bamboo biochar was done at Tadom Hill Resorts, Selangor, Malaysia

Figure 3. Bamboo biochar in granular sizes

Figure 4. Laboratory ball mill machines used to grind bamboo biochar into powder size (75 microns)

Figure 5. Bamboo biochar powder (BCP) sieved to 75 μm

From Table 1, it was recorded that the total usage of raw materials in producing sixty cube samples (50mm x 50mm x 50mm) was 8.525 kg of sand, 3.130 kg of water, 7.515 kg of cement, 0.270 kg of BCP, and 30 ml of superplasticiser (SP). Moreover, Table 2 shows 136.350 kg of sand, 50.110 kg of water, 120.240 kg of cement, 4.32 kg of BCP, and 500 ml of SP used in producing thirty beam samples (100mm x 100mm x 400mm). When the mortar mixture was added with bamboo charcoal powder (BCP), it was seen that the wet mixture was too sticky due to the porous properties of BCP that absorb water faster. Hence, a superplasticiser was added to the mixture to make it more workable and avoid the honeycomb of the mortar specimens.

Mortar mixtures were hand-mixed in a covered room with an average temperature of 28 ± 2°C. Sand and Ordinary Portland Cement (OPC) were first mixed until the dry mixture was nearly homogenous. It was continuously mixed, and then water was poured into the dry mixture. When a homogenous wet mortar mixture was achieved, a small amount of superplasticizer was and lastly, the mixing process slowly with BCP. It was indicated by visually the null presence of uncoated particles or any dry component. After the mixing process, the wet mixture was cast into 50 mm silicone cube moulds and compacted using a tray. The moulds would be kept for 24 hours at room temperature before they were demoulded. Hardened mortar bamboo biochar powder (MBCP) cubes were then cured in a curing tank until the testing day for density, upv test, water absorption test and compressive strength test on day-7 and day-28. Fig. 7 shows the hardened state of the cube mortars used in this study. Next, is the hardened state of MBCP prisms, Fig. 8. The mix proportions investigated in this research for sixty cube mortars and thirty prism mortars are presented in Table 1 and Table 2.

2.5. Compressive Strength Test

The strength performance of the hardened mortar was evaluated for relative compressive strength and volume of voids as per ASTM C109/C109M-20b [18]. A Universal Testing Machine (UTM) was used to test the compressive strength of hardened mortar. All hardened mortars were subjected to testing for 7 and 28 days of curing, with the mean value taken from three cubes. During the testing, specimens should be placed in the machine with the load should be applied to the opposite sides of the cube casting. The load was applied gradually without shock and continuously at 0.2 MPa/s rate until the specimen failed.

The maximum load was automatically recorded at this point of failure, and the type of failure was manually identified.

Figure 6. XRF analysis using Phywe XR 4.0 X-Ray instrument

Figure 7. Hardened state of cube mortars

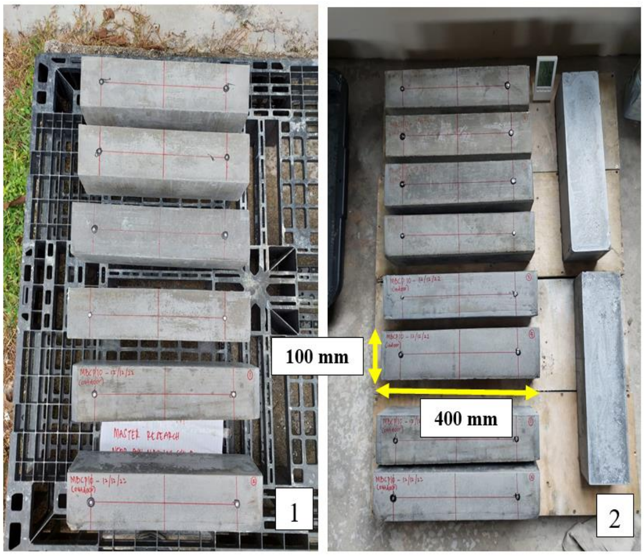

Figure 8. Hardened state of prisms mortar (1) outdoor, and (2) indoor conditions.

2.6. Water Absorption Test

The water absorption test measures the rate of water absorption (sorptivity) of both the outer and inner mortar surfaces. This test was conducted according to ASTM C1403-13 [19]. At first, the 50-mm cube specimens were removed from the moulds at 7 and 28 days after casting and dry them in the oven 110 °C for at least 24 hours. Testing began within 24 hours of the specimens reaching room temperature. The water absorption container was positioned on a stable, flat surface, and the specimens were arranged within it, so their cast top faces touched the support structures. There was at least 12 mm of space between each specimen and at least 25 mm between the specimens and the container's walls.

2.7. Ultrasonic Pulse Velocity Test

The Ultrasonic Pulse Velocity (UPV) test served as an on-site, non-invasive method for evaluating the integrity and quality of mortar. This procedure was applied to samples of hardened mortar after curing periods of 7 and 28 days. The recommended path length for the specimen according to ASTM C597-16 (2016) was from 50-mm minimum to 15-m maximum to ensure precision and accuracy [27]. Due to the small specimen tested with a 50-mm cube size, the accuracy of the test results was controlled by ensuring the frequency of ultrasonic pulse transmission within the minimum range of 50 to 60 Hz. To ensure consistent transit times, an adequate amount of coupling agent (petroleum jelly), and pressure needs to be applied to the transducers [28].

2.8. Drying Shrinkage Test

Drying shrinkage is directly linked to the decrease in mortar volume, which corresponds with the amount of water lost. As the mortar undergoes hydration, the quantity of water in its tiny capillaries notably reduces, leading to shrinkage. This research focused on observing the impact of BCP on drying shrinkage over a period of 150 days. The dimensions of the prism specimens used in this study adhered to the ISO 1920-8 standard procedure, measuring 100 mm x 100 mm x 400 mm [29]. Throughout the first 30 days, and then extending up to 150 days, data regarding drying shrinkage was collected from a demec gauge, Fig. 9. While for the data of relative humidity and temperature for both outdoor and indoor conditions were meticulously recorded by using a hygrometer monitor, Fig. 10, with a daily frequency during the initial 30 days followed by subsequent intervals until the conclusion of the 150 days study period. Moreover, the specified limit of length changes for drying shrinkage of mortar according to ASTM C596-18, should be at and no more than 0.10% at 50 days, 0.15% at 100 days, 0.20% at 150 days, and approximately not exceed 500v micro strains at 150 days [30].

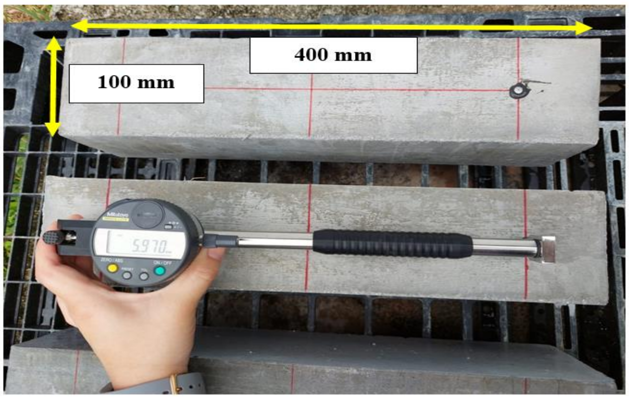

Figure 9. Measurement of drying shrinkage for mortar prism

Figure 10. Measurement of relative humidity and temperature for (1) indoor and (2) outdoor exposure for 150 days study period by using a hygrometer

3. RESULTS AND DISCUSSION

3.1. Chemical Oxide Composition

The chemical composition of bamboo biochar powder (BCP) was analysed using an x-ray fluorescence test (xrf test) and summarised in Table 3. BCP is mainly composed of magnesium oxide (MgO), aluminium oxide (Al2O3), silicon dioxide (SiO2), phosphorus pentoxide (P2O5), sulphur trioxide (SO3), chlorine (Cl), potassium oxide (K2O), calcium oxide (CaO), manganese (II) oxide (MnO), iron (II) oxide (Fe2O3), zinc oxide (ZnO), and rubidium oxide (Rb2O). The chemical composition of BCP revealed that it boasts a substantial SiO2 content, making up 38.1% of its composition, with K2O as the second most prominent element at 24.7%. The BCP also consisted of 20.6% Fe2O3, 12.5% CaO, 5.34% SO3, 2.97% P2O5, and 1.55% Al2O3. To qualify as a class C pozzolan according to ASTM C618-19 standards, the cumulative content of SiO2, Fe2O3, and Al2O3 should be at least 50% [25]. The total of these three oxides in this BCP was recorded at 60.25%, significantly achieving the required threshold of 50% for class C pozzolan. Consequently, the BCP could be considered a suitable replacement for cement in mortar mixtures [7].

3.2. Density, UPV, Compressive Strength, & Water Absorption

Recorded values of density and compressive strength test against the percentage of BCP for all five mixtures on day 7 and day 28 are shown in Fig. 11 and Fig. 12.

Table 1. Mix proportion details of cube mortars with BCP

Batch	Water-Cement Ratio	Sand (kg)	Water (kg)	Cement (kg)	BCP (kg)	SP (ml)	Total Samples
MBCP0	0.40	1.705	0.626	1.557	0	6	12
MBCP5	0.40	1.705	0.626	1.530	0.027	6	12
MBCP10	0.40	1.705	0.626	1.503	0.054	6	12
MBCP15	0.40	1.705	0.626	1.476	0.081	6	12
MBCP20	0.40	1.705	0.626	1.449	0.108	6	12

Table 2. Mix proportion details of prism mortars with BCP

Batch	Water-Cement Ratio	Sand (kg)	Water (kg)	Cement (kg)	BCP (kg)	SP (ml)	Total Samples		
							Outdoor	Indoor	Expansion
MBCP0	0.40	1.705	0.626	1.557	0	6	2	2	2
MBCP5	0.40	1.705	0.626	1.530	0.027	6	2	2	2
MBCP10	0.40	1.705	0.626	1.503	0.054	6	2	2	2
MBCP15	0.40	1.705	0.626	1.476	0.081	6	2	2	2
MBCP20	0.40	1.705	0.626	1.449	0.108	6	2	2	2

Table 3. Chemical oxide composition of BCP

No.	Composition	Weight Percent, %	No.	Composition	Weight Percent, %
1	SiO_2	38.1	7	Al_2O_3	1.55
2	K_2O	24.7	8	Cl	1.07
3	Fe_2O_3	20.6	9	MgO	0.99
4	CaO	12.5	10	MnO	0.86
5	SO_3	5.34	11	Rb_2O	0.54

6	P_2O_5	2.97	12	ZnO	0.38

There was a clear pattern of decreasing density and compressive strength as the percentage replacement raised for all mortar mixtures.
From Fig. 5, MBCP0 recorded 2173.60 kg/m3 for density on day 7 while 2182.93 kg/m3 for day 28, MBCP5 recorded 2099.47 kg/m3 for density on day 7 while 2105.87 kg/m3 for day 28, MBCP10 recorded 2039.47 kg/m3 for density on day 7 while 2069.60 kg/m3 for day 28, MBCP15 recorded 2028.27 kg/m3 for density on day 7 while 2024.80 kg/m3 for day 28, MBCP20 recorded 1942.93 kg/m3 for density on day 7 while 1929.33 kg/m3 for day 28. Density decreased as the percentage of BCP increased with the increase in age of curing. The decrease in density with an increase in BCP replacement could be ascribed to the fact that BCP was lighter than cement in the mix, hence, compatible with the findings from previous research that states increasing natural fibre content in composite materials, decreases the density of the composite [15]. As a non-reactive material, BCP does not participate in the hydration process of cement paste.

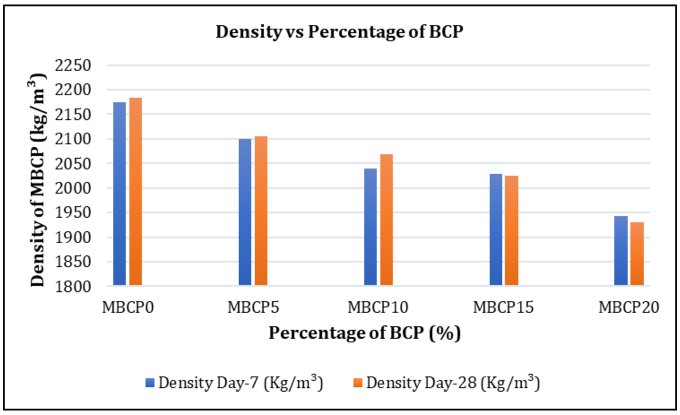

Figure 11. Experimental results density vs percentage of BCP for day 7 and day 28

Apart from that, in Fig. 9, MBCP0 recorded 41.71 MPa for compressive strength on day 7 while 48.12 MPa for day 28, MBCP5 recorded 19.93 MPa for compressive strength on day 7 while 29.03 MPa for day 28, MBCP10 recorded 35.17 MPa for compressive strength on day 7 while 46.09 MPa for day 28, MBCP15 recorded 31.57 MPa for compressive strength on day 7 while 41.31 MPa for day 28, MBCP20 recorded 20.56 MPa for compressive strength on day 7 while 25.40 MPa for day 28. From the result recorded, the compressive strength increased in the age of curing and decreased as the percentage of BCP increased. The increase in strength with the age of curing was due to the hydration of cement and the pozzolanic reaction of BCP in the mortar [4]. However, the strength recorded decreased along with the increase in BCP replacement could be due to the reaction mechanism of BCP, in which dilution of cement slower the strength development from the pozzolanic reaction, hence proving the decreased strength of MBCP. BCP is fragile and its strength is also low, and then the skeleton formed is fragile [15]. In this case, the hardened pastes with various BCP percentage replacements are provided with lower strength than the control, MBCP0. However, MBCP10 and MBCP15 still managed to achieve 40 MPa above on day 28.

This research recorded lower compressive strength as the biochar ratios increased. This happened due to the low temperature for the pyrolysis process that the bamboo biochar undergoes at only 200 to 600°C, as mentioned in sub-topic 2.2. The reduction in compressive strength of mortar bamboo biochar powder (MBCP) is also due to the class C pozzolan according to ASTM C618-19 standards, the cumulative content of SiO_2, Fe_2O_3 and Al_2O_3 should be at least 50% [25]. The total of these three oxides in the bamboo biochar powder (BCP) was recorded at only 60.25%. BCP did not achieve the standard requirement for the best pozzolan type, which was pozzolan type N that needed to exceed 70% of the total three oxides, SiO_2, Fe_2O_3 and Al_2O_3. Previous researchers [31] mentioned that during pyrolysis at lower temperatures, the process did not completely transform the silica-rich components found in the bamboo biochar, into silicon dioxide (SiO_2). This happened due to the reactions needed to convert silica into SiO_2 were not as effective at the low temperature, leading to a reduced production of SiO_2. Consequently, the BCP still can be considered a suitable substitute for cement as the compressive strength of 10% replacement ratio, MBCP10, achieved the targeted high-strength mortar with 46.09 MPa.

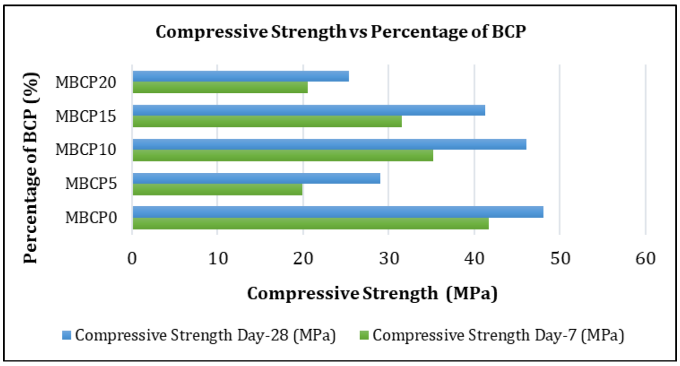

Figure 12. Experimental results compressive strength vs percentage of BCP for day 7 and day 28

Furthermore, results for upv against the percentage of BCP in 7- and 28-day, Fig. 13, shows a considerable rise following the establishment of this solid percolation threshold, as the stiffness of the cement paste is heavily dependent on the solid phase link. MBCP0 recorded 2.44 km/s for upv test on day 7 while 3.46 km/s for day 28, MBCP5 recorded 1.44 km/s for upv test on day 7 while 2.80 km/s for day 28, MBCP10 recorded 1.77 km/s for upv test on day 7 while 3.38 km/s for day 28, MBCP15 recorded 1.65 km/s for upv test on day 7 while 3.17 km/s for day 28, MBCP20 recorded 1.55 km/s for upv test on day 7 while 2.13 km/s for day 28. As a result, it was determined why ultrasonic pulse velocity values for all mortar mixes on day 28 were greater than mortar mixes on day 7. Beyond this stage, the impact of the solid phase on the upv takes precedence over the influence of air bubbles. The stiffness of a material has a significant impact on its upv. Once the relationship between upv and solid phase connection is established, further attributes like stiffness and strength may be acquired [21]. The ultrasonic velocity is not very sensitive to the formation of structure in the paste throughout the suspension phase.

The water/air phase, particularly the air bubbles in the water, is the major component determining the upv. The joining of smaller particles leads to clusters that create a percolating solid network as cement grains eventually disintegrate and nucleate. The route of ultrasonic pulse propagation changes from liquid to solid.

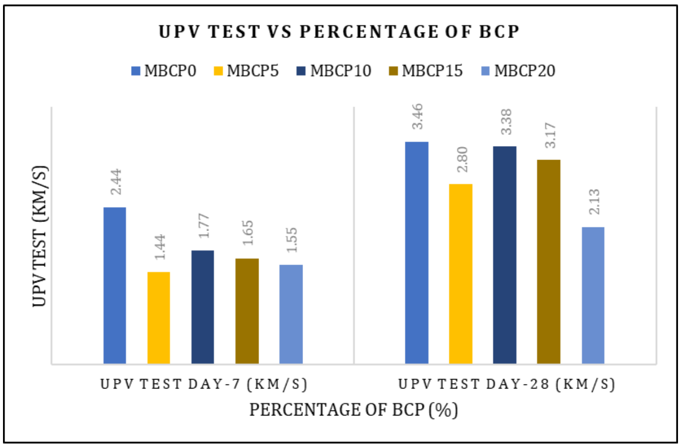

Figure 13. Experimental results upv test vs percentage of BCP for day 7 and day 28

According to water absorption results in Fig. 14, MBCP0 recorded 1.00% for water absorption test on day 7 while 2.00% for day 28, MBCP5 recorded 2.40% for water absorption test on day 7 while 3.10% for day 28, MBCP10 recorded 3.30% for water absorption test on day 7 while 4.60% for day 28, MBCP15 recorded 4.50% for water absorption test on day 7 while 6.10% for day 28, MBCP20 recorded 5.50% for water absorption test on day 7 while 7.50% for day 28. The water absorption test is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of the material. The amount of water absorbed by mortar mixes depends on the water tightness or waterproofness of the mixes [22]. All mixes were subjected to water absorption tests at the end of the wet curing period of 7 and 28 days after demoulding. Moreover, from the results, the water absorption rate of all mortar mixtures increased gradually until the end of 28 days. This happened due to the result of reduction of cement content resulting in less quantity for hydration [24].

The water absorption increased according to the addition of bamboo biochar powder (BCP). This trend was recorded in a previous study that used wood biochar in cement mortar [32]. They recorded that adding 1-10% wood biochar, created at a low temperature of 400 °C, affected the capillary water absorption of mortar over time. The water absorption rate was 10% lower in the 1% biochar mortar due to biochar's hydrophilicity, which increased resistance against water penetration, slowing absorption rates. Nonetheless, adding more biochar increased the absorption coefficient significantly with 3%, 5%, and 10% additions causing increases of 16%, 39%, and 88%, respectively. This was likely due to biochar creating more voids and larger pores, enhancing the water absorption rates. Moreover, Gupta & Kua [33] also mentioned that biochar produced at lower temperatures, 400°C and 500°C, enhanced the capillary water absorption more effectively. Especially with more than 3% biochar addition in mortar mixtures, compared to biochar produced at higher temperatures, 700°C and 800°C.

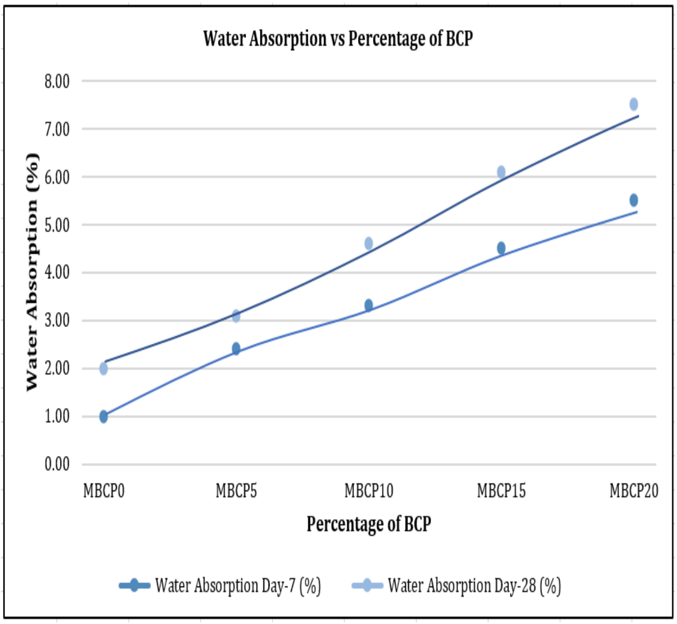

Figure 14. Experimental results water absorption test vs percentage of BCP for day 7 and day 28

3.3. Shrinkage Strain

Drying shrinkage is strain associated with loss of moisture from the mortar by evaporation of water or hydration of cement. The change in the volume of the mortar is related to the volume of water lost. The loss of free water from mortar may induce shrinkage. As the hydration process of the mortar continues, the water in the small capillaries is reduced significantly. This study was conducted to examine the effects of bamboo charcoal powder (BCP) on drying shrinkage for up to 150 days. The size of beam specimens would be 100x100x400mm, according to the ISO, 1920-8. The drying shrinkage readings had been recorded daily for the first 30 days and continued for 30 days after reaching 150 days. The results of shrinkage and expansion for all mixtures outdoor and indoor are shown in Fig. 15, Fig. 16, and Fig. 17. Table 4 shows the overall recorded data of shrinkage strains from day 1 until day 150. From the recorded data, the average day-time temperature and relative humidity were 29.5°C and 83.9%, respectively. The shrinkage strain results shown in Table 4 is referred to as drying shrinkage. The shrinkage was recorded up until 5 months. From all the drying shrinkage results recorded, the sample with the highest percentage replacement of BCP which was MBCP20 recorded the highest shrinkage value for outdoor, indoor, and expansion, with 487x10-6m, 191x10-6m, and 300x10-6m. Next, MBCP5 recorded the lowest shrinkage strain at indoor exposure with 144x10-6m, while MBCP10 had the lowest shrinkage strain at outdoor exposure with 330 x10-6m, and MBCP0 the lowest shrinkage strain at expansion with 210x10-6m. Finally, a low percentage replacement of BCP in cement mortars is highly effective in controlling and mitigating the susceptibility to drying shrinkage of cement mortar samples.

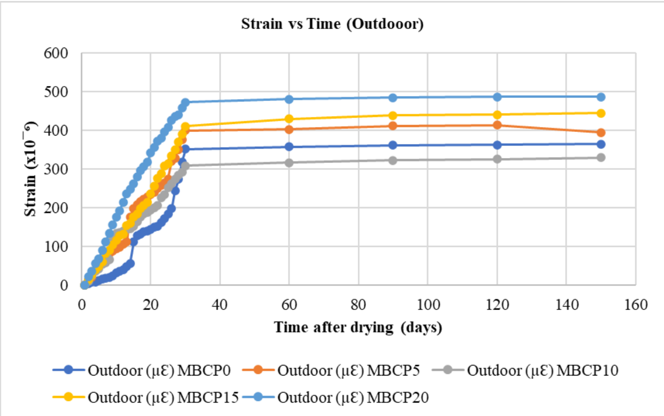

Figure 15. Shrinkage strain of MBCP beams at outdoor exposure

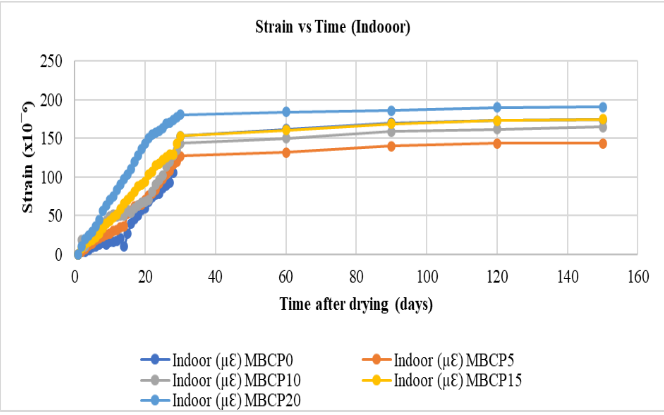

Figure 16. Shrinkage strain of MBCP beams at indoor exposure

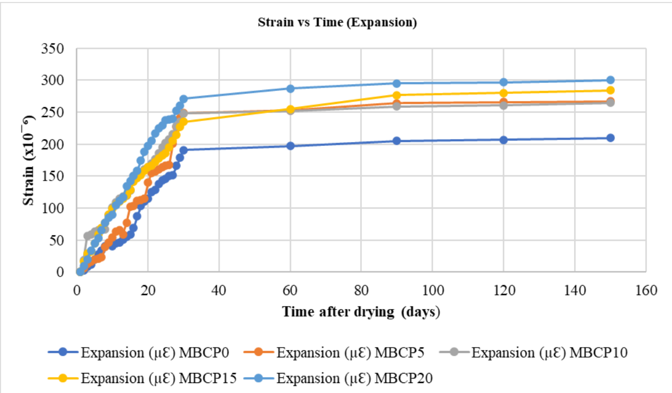

Figure 17. Shrinkage strain of MBCP beams in expansion

4. CONCLUSION

In summary, this comprehensive study was undertaken to explore the potential and applicability of BCP as a sustainable additive in mortar composition. The objectives of this study were successfully achieved, leading to several imperative findings and conclusions.

The first objective of this study was to evaluate the chemical and physical properties of BCP. The cumulative amount of SiO_2, Fe_2O_3, and Al_2O_3 in BCP surpassed the 50% benchmark stipulated for Class C pozzolans by ASTM C618-19 (2019) standards, reaching 60.25% in total.

This percentage suggested that BCP was able to replace cement in a few proportions, offering a potential route for greener construction materials.

In the second objective, the mechanical properties of MBCP in a hardened state were determined, considering various percentages of BCP (0%, 5%, 10%, 15%, and 20%) as a cement substitute. The results showcased a nuanced relationship between BCP content and mortar performance. Although higher percentages of BCP reduced the density and compressive strength of the mortar cube specimens, they also contributed to an increment in UPV and water absorption. These findings underscored the potential of BCP to be a valuable component in mortar mixtures tailored for specific construction applications for high-strength mortar such as grouting.

The third objective investigated the effect of BCP on mortar shrinkage when subjected to indoor and outdoor conditions under tropical climates. Analysis of shrinkage strain yielded significant insights, where 10% BCP (MBCP10) appeared as the optimum percentage cement replacement for outdoor conditions, in which it reduced the shrinkage of mortar with 330 x 10-6 m, where mortar control recorded shrinkage with 365 x 10-6 m. While 5% BCP (MBCP5) and 10% BCP (MBCP10) recorded the most suitable percentage as cement replacement in the mortar mixes for indoor conditions, where MBCP5 with 144 x 10-6 m, and MBCP10 with 165 x 10-6 m lower than the mortar control with 150 x 10-6 m, in which could mitigate shrinkage strain, particularly in indoor conditions. Moreover, the highest shrinkage strain was recorded in both outdoor and indoor conditions by mortar prisms containing 20% BCP. Although MBCP20 recorded the highest shrinkage for both outdoor and indoor conditions, this research study was still can be accepted as the specified limit of drying shrinkage of mortar according to ASTM C596-18 (2018), should not exceed 500 microstrains at 150 days. These results emphasised the critical impact of environmental conditions and BCP content on the shrinkage behaviour of mortar.

Based on the findings of this research study, recommendations for future studies include a long-term mechanical properties assessment for cube bamboo biochar mortar (MBCP). Further exploration into the long-term mechanical properties of MBCP is recommended. Extending the analysis period to 150 days would match the timeframe used for drying shrinkage tests, providing a comprehensive understanding of the mortar's performance in the long-term period. This is crucial because some characteristics, like compressive strength and density, may change as the mortar continues to cure and age. Additionally, future studies could also focus on developing statistical or modelling analyses to predict drying shrinkage behaviour. Statistical and modelling analyses, such as regression models or even machine learning algorithms. These could yield valuable predictive tools for construction material design, allowing for the optimisation of BCP ratios in mortar mixtures.

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