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ENHANCING SUSTAINABILITY IN CEMENTITIOUS COMPOSITES WITH ULTRAFINE BURNT CLAY BRICK POWDER AND RICE HUSK ASH

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Article Info

Abstract
The construction sector is under intense pressure to minimize its carbon footprint and reliance on nonrenewable raw materials, particularly Ordinary Portland Cement (OPC). This study looks at the possibilities of ultrafine clay brick powder (CBP) and rice husk ash (RHA) as sustainable supplemental cementitious materials (SCMs). CBP, produced from building and demolition waste, and RHA, an agro-industrial byproduct, were tested in mortar composites with varied fineness and replacement amounts to see how they affected the fresh and hardened qualities. A detailed experimental program, including setting time, workability, flow, and compressive strength tests, was performed following ASTM standards. Results revealed that CBP and RHA significantly influence the hydration process, with optimum performance observed at 5–15% replacement levels depending on particle size. Particularly, finer CBP (#200) showed improved pozzolanic activity, while RHA enhanced early-age strength and matrix densification. The study confirms that integrating CBP and RHA can reduce cement consumption and CO_2 emissions, promoting circular economy principles in construction. This research enhances the expanding corpus of information about sustainability cementitious composites, offering practical insights for eco-friendly construction practices.

Keywords:
Brick Powder, Ultrafine Material, Rice Husk Ash, Supplementary Cementitious Materials, Pozzolanic Activity, Construction and Demolition Waste, Compressive Strength.

1. Introduction

The rising concentration of greenhouse gases and the associated phenomenon of global warming pose enormous challenges to the globe today. Ice melting is at an all-time high, and natural disasters are becoming more frequent and intense. The phenomenon of climate change has been unequivocally demonstrated to be a direct result of human activities, specifically the injection of large amounts of greenhouse gases into the natural environment. If the levels of greenhouse gases continue to increase in the atmosphere, the global surface temperature will rapidly escalate beyond previous levels. A large portion of the warming in recent years is likely due to human activities such as manufacturing, transportation, mining, and construction. During the industrial age, the construction sector played a pivotal role in contributing significantly to the increase in carbon emissions within our environment. The primary usage of energy and raw materials on a global scale is largely associated with construction, which represents almost half of the overall consumption. The various activities involved in the construction processes, such as land clearing, operation of equipment engines, demolition, burning, and utilization of hazardous chemicals, significantly contributed to environmental pollution.

Furthermore, the rapid expansion in global population raises the demand for new buildings and infrastructure facilities. Due to the fast pace of urban development, a significant amount of CDW is being generated around the world (López Ruiz et al., 2020) (Islam et al., 2019) (L. Wang et al., 2024). Reports indicate that the European Union and the United States generate about 800 and 700 million tons of Construction and demolition waste (CDW) annually. China generates more than 1800 million tons of CDW per year (Ma & Hao, 2024) (H. Duan & Li, 2016) (Aslam et al., 2020).

CDW is frequently disposed of by discarding and burying, resulting in multiple societal and ecological concerns, including hazardous risks and contamination of earth and water resources (Molla et al., 2025) (Chen et al., 2022). CDW is mostly consisting of concrete, brick, glass, ceramic, steel, plastic, and wood trash. Concrete and brick debris account for more than 80% of CDW, whereas the other constituents, glass and steel waste, are in smaller quantities and have a dedicated recycling method (Sormunen & Kärki, 2019) (Arachchige). Therefore, enhancing the efficiency of the reusing waste concrete and brick is an effective approach for mitigating the quantity of CDW. This approach yields recycled concrete powder (RCP) and recycled clay brick powder as principal recycled products (Zhang et al., 2023). Cement, the principal component in the creation of concrete, is a necessary building material. China has remained the global leader in cement output since 1985, producing 60% of the world's cement in 2012 (Cement, 2013). Currently, China is the world's top cement producer and consumer. China's cement production reached 1.87 billion metric tons in 2010. Cement production in China was 1.87 billion metric tons in 2010 (Xu et al., 2012). Global cement production is expected to hit 8.2 billion tons by 2030, according to the World Cement Association (Tkachenko et al., 2023).

Due to urbanization, its need is going to increase day by day at a faster rate. Cement production worldwide contributes more than 7% to global greenhouse gas emissions, making it one of the top emitters (Tkachenko et al., 2023). The manufacture of one metric ton of cement typically releases approximately one metric ton of carbon dioxide (CO_2) into the atmosphere (He et al., 2020). The escalation of CO_2 emissions has caused in a substantial increase in global temperature, exceeding the threshold and leading to a profound alteration in climate. Cement manufacture emits not only CO_2, but also NO_2 and SO_3, which exacerbate the greenhouse effect and acid rain (Ashraf et al., 2017; Rashad & Zeedan, 2011; D. Wang et al., 2018). There is a pressing need for research and identification of various SCM to reduce reliance on cement. The use of SCM is thought to be the most practicable and cost-effective strategy to cut CO_2 productions in the cement sector. Replacing cement with SCM, either partly or completely, supports effective CDW management.

Research indicates that crushed clay brick can act as an alternative to aggregate in concrete. The influence of clay brick aggregate on workability, strength, dimensional integrity, and durability has been well researched. Currently, little research has been conducted to investigate the behavior of CBP as a binder material CBP in mortar and concrete. The objective of this research is to examine the behavior of ultrafine CBP and RHA as partial substitutes for cement, as well as to assess the influence of CBP and RHA fineness as cementitious material substitutes. This work has the capacity to raise knowledge about the use of CBP and RHA as cement alternatives. This can result in a reduction in cement output, which contributes significantly to sustainability and environmental preservation.

Materials and Methods:

Materials:

2.1.1. Clay Brick Powder:

Bricks from demolition sites have been looked into as a potential alternative to cementitious materials (O'Farrell et al., 2000; Toledo Filho et al., 2007; Turanli et al., 2003; Wild et al., 1997). Many times, the behavior of mortars with and without partial replacement of CBP has been compared, and it has been found that as the amount of CBP is increased while replacing cement, overall porosity increases and strength decreases (Gonçalves et al., 2009). However, the 90-day replacement compressive strengths are up to 20% higher or on par with the results from a plain cement control mix (M. O'Farrell and S. Wild). Furthermore, the hydraulicity of the mortar is strongly impacted by the fire temperature of the bricks and the fineness of the powder (Baronio & Binda, 1997).

This investigation aimed to analyze the pozzolanic potential of CBP for partial cement replacement at multiple levels. CBP was derived from waste bricks piled at wasteland areas, near brick furnaces, and from dust of broken bricks in Lahore city. To separate brick debris from concrete waste, Pakistan employs a variety of procedures, including selective dismantling, manual and mechanical separation techniques were used, with mechanical separation proving relatively more efficient. After collecting the clay bricks, they were broken in a crusher to make aggregate, which was then milled in a ball mill to produce CBP. Different CBP fineness levels were attained by tuning the grinding equipment and altering the time. Brick debris was initially milled using a regular ball mill for 30 minutes to produce high-fineness CBP, which was then processed in a planetary ball mill for 90 minutes to further increase the fineness of CBP. A further increase in the grinding time, in particular, has no discernible effect on the lowering of the fineness of CBP. The CBP was further processed to control quality via sieving to remove particles exceeding 100 μm and heating in an oven at 105°C for 8 hours to dry out moisture. Two samples, i.e., one having passed through the ASTM sieve 100 (CBP1) and the other having passed through the ASTM sieve 200 (CBP2), were prepared in sufficient amounts for further working on it. Figures 1 and 2 show the preparation process and particle size analysis of CBP1 and CBP2.

The chemical composition of CBP1, CBP2, OPC, and RHA was analyzed, as shown in Table 1. The chemical analysis of CBP1 and CBP2 revealed almost the same composition of minerals, which was evident. CBP contains major minerals and oxides such as SiO_2, Fe_2O_3, CaO, and Al_2O_3. The CBP may erve as an effective pozzolanic additive to be utilized as a partially replace cement because the cumulative proportion of SiO_2, Fe_2O_3, and Al_2O_3 is 83.17%, which is greater than 70% and even more than 80%. As per (ASTM D854), CBP has a specific gravity of 2.17 and density of 1250 kg/m³, which makes it lighter than cement.

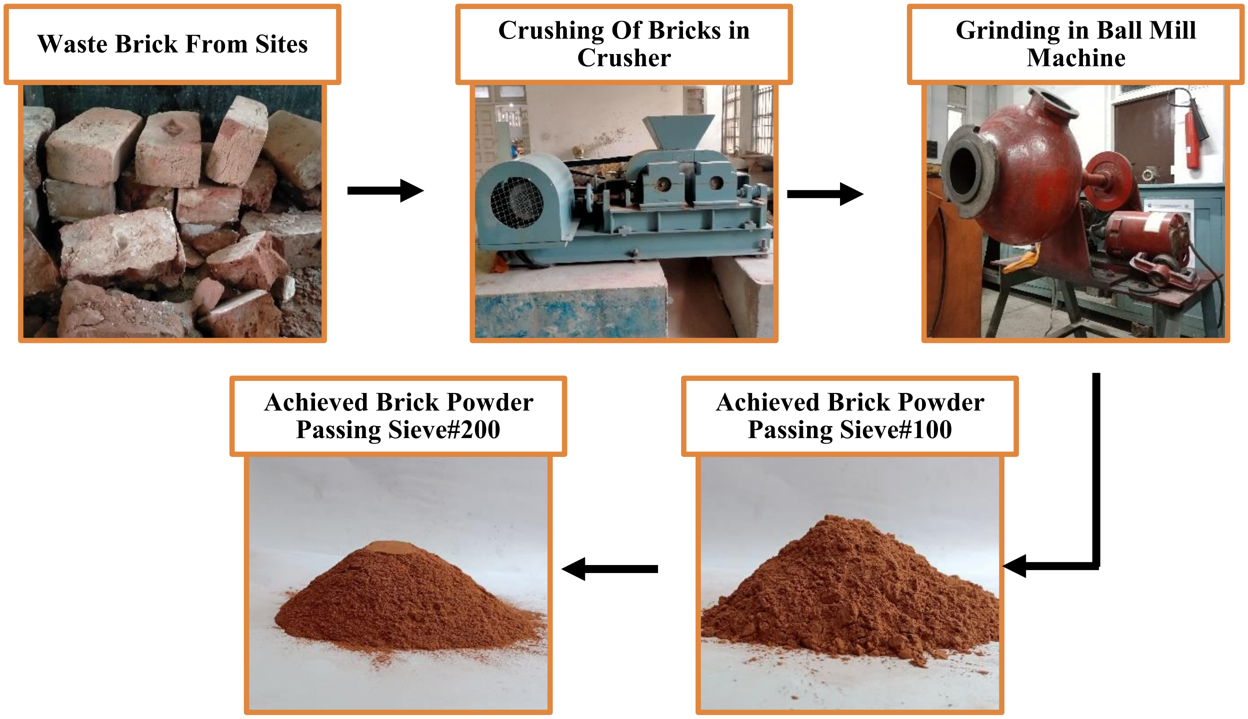


Figure 1: Waste Brick Powder Producing Procedures

According to Kurdowski, in moist conditions, fine-grained SCMs with reactive SiO_2 or Al_2O_3 can react with Portlandite ($Ca(OH)_2$) to form additional C-S-H gel. As a result, there is less Portlandite available. Pozzolanic materials are these SCMs, which have Portlandite reactivity and low lime content.

2.1.2. Cement:

The Cement used in this research was OPC - Type I of Grade C-53 and satisfies the specification (ASTM C150, 2012). Tables 1 and 2 display its chemical and physical characteristics.

2.1.3. Water:

Portable water from the concrete laboratory of the structural engineering division of the Civil Engineering Department, UET Lahore, was used in this research.

Table 1: Chemical composition of OPC, CBP and RHA.

Chemical Compounds	OPC	#100 Passing	#200 Passing	RHA
SiO_2	20.40	62.40	61.84	71.5
CaO	60.30	0.82	1.04	2.94
Fe_2O_3	3.25	5.52	5.68	0.38
Al_2O_3	5.28	15.25	14.80	1.02
MgO	1.75	2.16	1.92	1
SO_3	2.37	0.48	0.43	0.51
L.O.I	5.16	0.561	0.532	20.91

Table 2: Physical characteristics of OPC, CBP and RHA.

Parameter	OPC	CBP1	CBP2	RHA
Specific Gravity	3.15	2.17	2.17	-
Density (Kg/m^3)	3150	2170	2170	
Consistency (%)	30	-	-	

2.1.4. Rice Husk Ash (RHA):

RHA is an agricultural waste material generated by burning husk at temperatures under 800 °C in a controlled environment. It generates 25% of ash with strong pozzolanic properties, consisting of around 85–90% non-crystalline silica and 5% aluminum oxide. According to Mehta, concrete with RHA demands more water to achieve a given consistency because of the porous structure of RHA particles. In one investigation, RHA from Indian paddy was reburned at 650 °C for one hour, resulting in a usable pozzolanic material having 87% amorphous silica and just 2.1% loss on ignition.

Rice husk combustion can occur under controlled or uncontrolled conditions. Rice husk was first burned in village open heaps at varying temperatures from 300 to 450 °C to generate ash (Endale et al., 2022). Burning the husk below 500 °C without control led to incomplete ignition and a notable presence of unburned carbon in the ash (Al-Khalaf & Yousif, 1984).

Methodology:

This study was conducted to gain deeper insight into the characteristics and fresh-state properties of CBP-based and RHA-based cement composite mortars at various percentages. The performance and quality of CBP and RHA-based composites are assessed and predicted by performing various tests and by determining the various physical properties, including workability, flowability, setting time, density, and compressive strength. At first, CBP1, CBP2, and RHA were prepared, and their physical and chemical properties, like density, specific gravity, water absorption, etc., were determined alongside the complete chemical analysis of OPC, CBP1, CBP2, and RHA. After preparing the necessary components, CBP and RHA mixes were produced at varying percentages. These mixes were then used to assess the fresh-state features of CBP and RHA-based mixes, including workability, setting time, flowability, and so on. Finally, 2 x 2-inch cubes were cast to determine the compressive strength of CBP and RHA-based mortars. In accordance with ASTM standards and procedures, all specimens were prepared and tested, as shown in Figure 2.

2.2.1. Mix Proportions and Samples Preparation:

In total, 26 CBP and RHA-based cement mixes were prepared, shown in table 3. Ten mixes of CBP (sieve # 100) at 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50% replacement were prepared. Similarly, 10 mixes of CBP (sieve # 200) and 5 RHA were prepared at the same percentages of replacement as CBP (sieve # 100). One mix was prepared without any replacement of CBP and RHA, which was used as a control. The mixes were prepared using an electronic mixer. The water-to-binder ratio was used as 0.44.

After preparing the mixes having different percentages of CBP and RHA, the various tests to determine the fresh-state properties, including but not limited to setting time test, Ve-be test, flow table test, were performed as per the ASTM standards, and then the mortar mixes were cast in two-by-two-inch cubes for performing the compressive strength tests.

Table 3: Mix Proportion of CBP & RHA with Cement

Sample	Mix Proportions (%)			
	Cement	CBP1	CBP2	RHA
CBP-0%	100	-	-	-
CBP1-05%	95	5	-	-
CBP1-10%	90	10	-	-
CBP1-15%	85	15	-	-
CBP1-20%	80	20	-	-
CBP1-25%	75	25	-	-
CBP1-30%	70	30	-	-
CBP1-35%	65	35	-	-
CBP1-40%	60	40	-	-
CBP1-45%	55	45	-	-
CBP1-50%	50	50	-	-
CBP-0%	100	-	-	-
CBP2-05%	95	-	5	-
CBP2-10%	90	-	10	-
CBP2-15%	85	-	15	-
CBP2-20%	80	-	20	-
CBP2-25%	75	-	25	-
CBP2-30%	70	-	30	-
CBP2-35%	65	-	35	-
CBP2-40%	60	-	40	-
CBP2-45%	55	-	45	-
CBP2-50%	50	-	50	-

CBP-0%	100	-	-	-
RHA-05%	95	-		5
RHA-08%	93	-		8
RHA-10%	90	-		10
RHA-12%	88	-		12
RHA-15%	85	-		15

Figure 2: Flowchart of Methodology

2.2.2. Casting and Curing:

After preparing various mortar mixes, casting of CBP and RHA-based cement mortars was done as shown in Figure 2. The cubes, having 2 x 2 inches dimensions, were prepared according to ASTM guidelines. Following (ASTM C31/C31M, 2019), the molds were cleaned, lubricated, and used for casting. All the casted cubes were placed in a standard curing room having T = 20 +_2 degrees Celsius for 1 day. The specimens were extracted from the molds after 24 hours and were put in a bathtub for 3, 7, and 28 days for proper curing.

2.2.3. Test Methods:

The characteristics of CBP and RHA-based cement mortars were evaluated in both fresh and hardened states. This study included setting time testing, flow table tests, fluidity tests, and compressive strength tests.

Slump Test:

The slump test was performed by the (ASTM C143, 2012). A cone with dimensions 30 cm (height), 10 cm (top), 20 cm (bottom), and 1.60 mm (thickness) was used for the slump test. Cement paste including CBP had initial and ultimate setting times determined by the code criteria. This test was performed using the Vicat device, which included a needle and an attachment.

Flow Test:

According to (ASTM C1445, 2013) to perform the spread test, a cone-shaped mold with a flat top must be filled on a flat, even surface. After removing the mold, the mortar's spread diameter is measured in two right-angle directions, and the mean was taken (Belaidi et al., 2012). Moreover, each mortar mix was employed to 25 blows to determine the workability of CBP mixes.

Fluidity Test:

The SCM mixes flow capacity was tested through a standard V-funnel flow test. The time between opening the funnel orifice and the first light visible through it was used to assess the SCM’s flow capacity (Belaidi et al., 2012).

Compressive Strength

Evaluation of compressive strengths in the paste were taken for curing durations of 3-, 7-, and 28-days using cube samples with dimensions 50 x 50 x 50 mm. Testing was carried out using a universal testing machine rated at 1500 kN (ASTM C109, 2020).

End Notes:

Other researchers have also noticed the cement particles flaky appearance and rough surface (Mohammed Al-Ani, 2015). Modified samples showed very little bleeding. Due to its greater mass per volume, cement drives water upward and settles heavier particles, causes bleeding. CBP particles are lighter than cement; hence slight reduction in bleeding was observed (Thomas, 2007). CBP, a pozzolanic substance, contributes delayed hydration. As pozzolanic activity was delayed and progresses over time, while mixing and placing, the water was available in an excess amount. This improved the workability of the CBP mixes (Rogers, 2011).

Results and Discussion:

Setting Time:

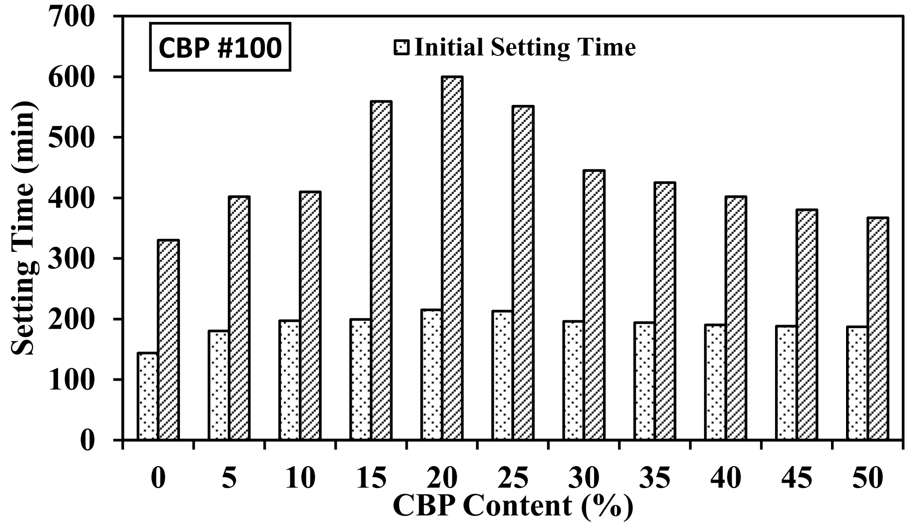
Figure 3 illustrates how CBP and RHA influence the early-age and ultimate setting response of cement paste. As demonstrated, the setting behavior of cement paste with varying amounts of CBP and RHA are longer than those for the control paste. In general, substituting varying proportions of ultrafine brick powder for cement had only a little impact on the cement paste's setting time.

Figure (a) shows that the trends for initial and final setup time gradually grew up to 20% replacing CBP, after which they declined. The highest ideal value of the early-age and final setting behavior was attained by replacing 20% of CBP (Sieve #100 Passing) with cement paste. When relative to the control mix, the early-age and final setting behavior of the 20% substituted cement mixture rose by 33.02% and 45%, respectively.

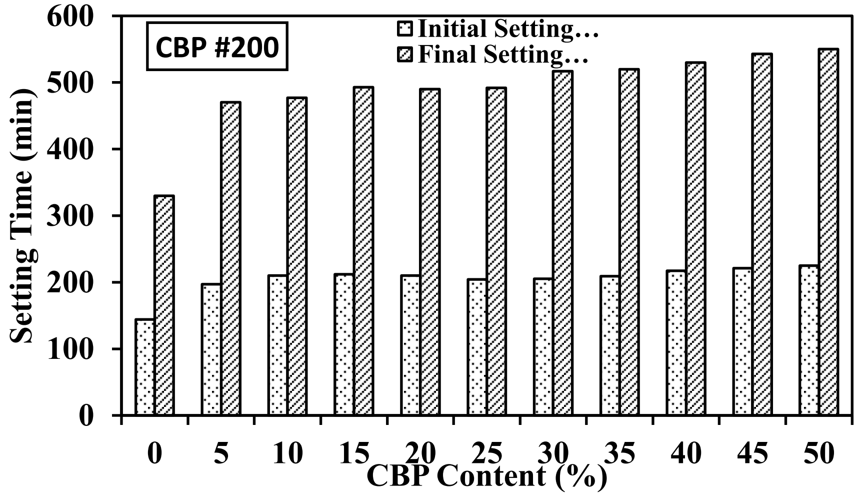
This waslargely because the cementitious materials initiate hydration right after mixing with water, constantly generating flocculent structures (Z. Duan et al., 2020). From 30% to 50% replacement, the initial & final setting time of the CBP replaced sample decreased due to the higher value of Al_2O_3, which plays an important role in controlling the setting time of the Sample. Because of the added waste brick's high-water absorption, the setting times of the cement paste dropped as its concentration increased. The chemical process is accelerated in the short term, which explains this (Naceri & Hamina, 2009).

From Figure (b), the maximum optimum value of initial & final time is taken at 50% replaced sample of cement paste with CBP (Sieve #200 Passing). The presence of SiO_2 in clay bricks results in porous structures, delaying the setting process (Lin et al., 2010a). Based on the findings of these researchers, the presence of porous structures within cement paste can hurt the degree of its stiffening, leading to prolonged setting times. In addition, Fe2O3, Na2O, and K_2O were assumed to increase the duration of setting (Wong & Kwan, 2008). This aspect could explain why partially refilled cement paste takes longer to set. The addition of recycled brick powder produces a diluting result and decreases the resulting products from cement hydration, which prolongs the setting time (He et al., 2021).

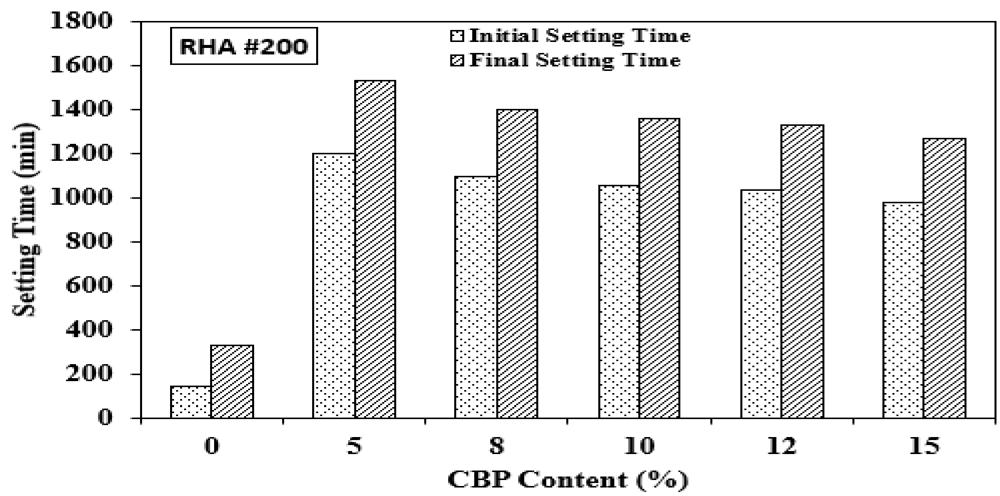
Figure (c) demonstrates the setting behavior of the control cement paste and partially replaced cement paste with different proportions of RHA (Sieve #200 Passing). The early-age and final setting behavior were greatly higher than compared of the control and CBP (Sieve #100 & 200 Passing) cement paste. By changing the proportion of RHA, the trend for the initial & final settings decreases gradually. This result is not according to standards, as it gives a very large value for setting times. According to ASTM regulations, the early-age and final setting behavior should be no more than 375 minutes and 10 hours, respectively (ASTM C191, 2021).



a) **Setting Time (Min) for Different Dosages of CBP (Sieve #100 Passing)**



B) Setting Time (Min) for Different Dosages of CBP (Sieve #100 Passing)



C) Setting Time (Min) for Different Dosages of RHA (Sieve #200 Passing)

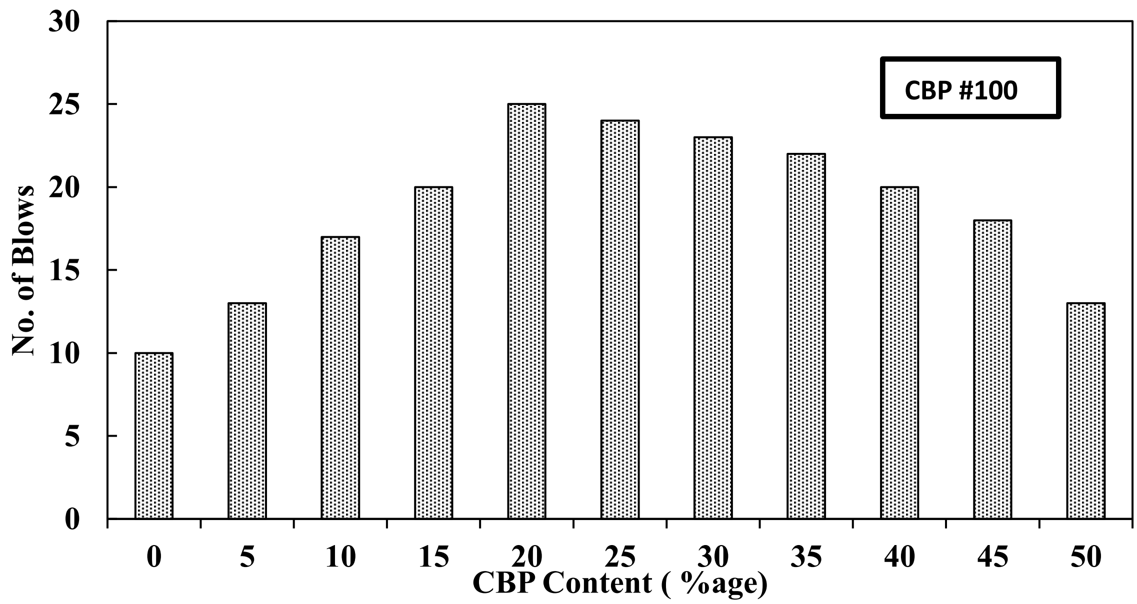
Figure 3: Setting time (min) for different dosages of CBP (#100 & #200) & RHA (#200) with Cement

Flow Table Test:

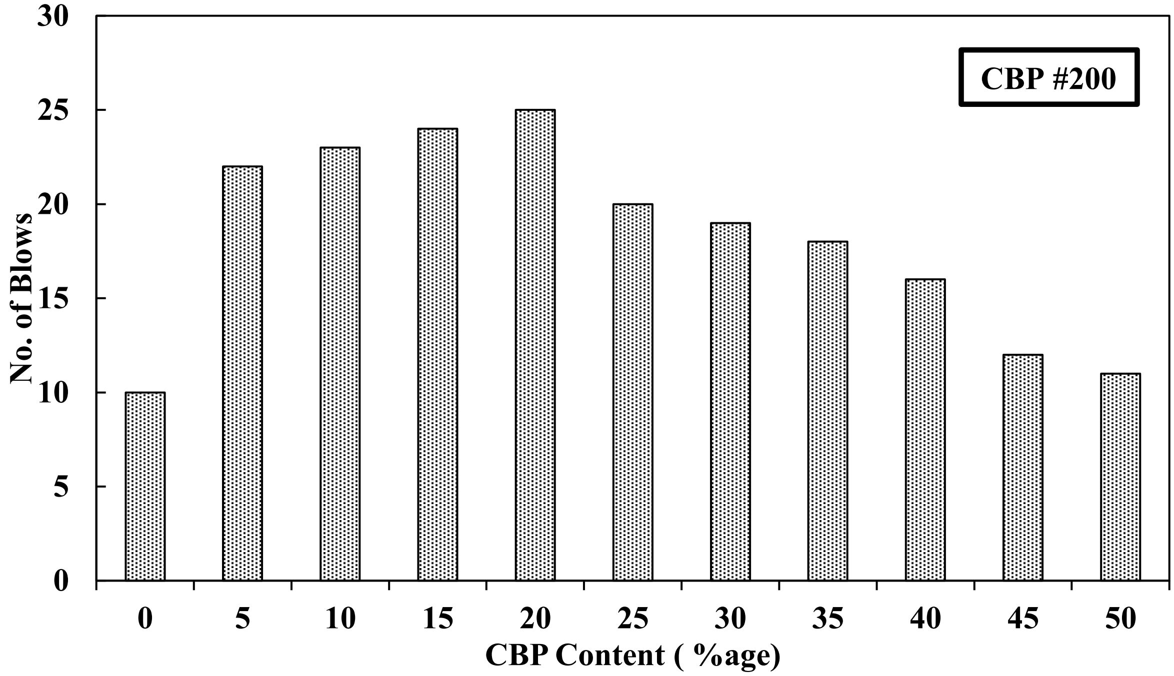
Figure 4 illustrates the influence of various percentages of CBP (Sieve #100 Passing), CBP (Sieve #200 Passing), and RHA (Sieve #200 Passing) on the workability of partially replaced cement pastes. The graphs are between the No. of blows required to fill the circular plate of the flow table with the partially replaced cement pastes and various percentages of partially replaced cement pastes with CBP (Sieve #100 Passing), CBP (Sieve #200 Passing), and RHA (Sieve #200 Passing). As evident, the workability of the partially replaced cementitious composites was reduced attributed to an expansion of the mortar surface and the increased partial inculcation of CBP1, CBP2, and RHA.

Figure 4(a) shows that as the percentage of CBP (Sieve #100 Passing) is increased in the partially replaced cementitious composites, the workability of the composites decreases up to 20% replacement. This is evident by the increase in the number of blows required before the area of the flow table base plate gets covered. This decrease in the workability of cementitious composites as CBP (Sieve #100 Passing) inclusion is increased mirrors the case of concrete and mortar described in prior studies (Aliabdo et al., 2014; Li et al., 2019). The drop in workability observed in CBP (sieve #100 passing) cementitious composites could be attributed to its high specific surface area (Kartini et al., 2012). The mixtures became stiffer with increasing CBP (Sieve #100 Passing) concentrations for a fixed w/b ratio. These experimental findings imply that the introduction of CBP (Sieve #100 Passing), which caused a reduction in workability, was due to its rough surface (Ge et al., 2015a).

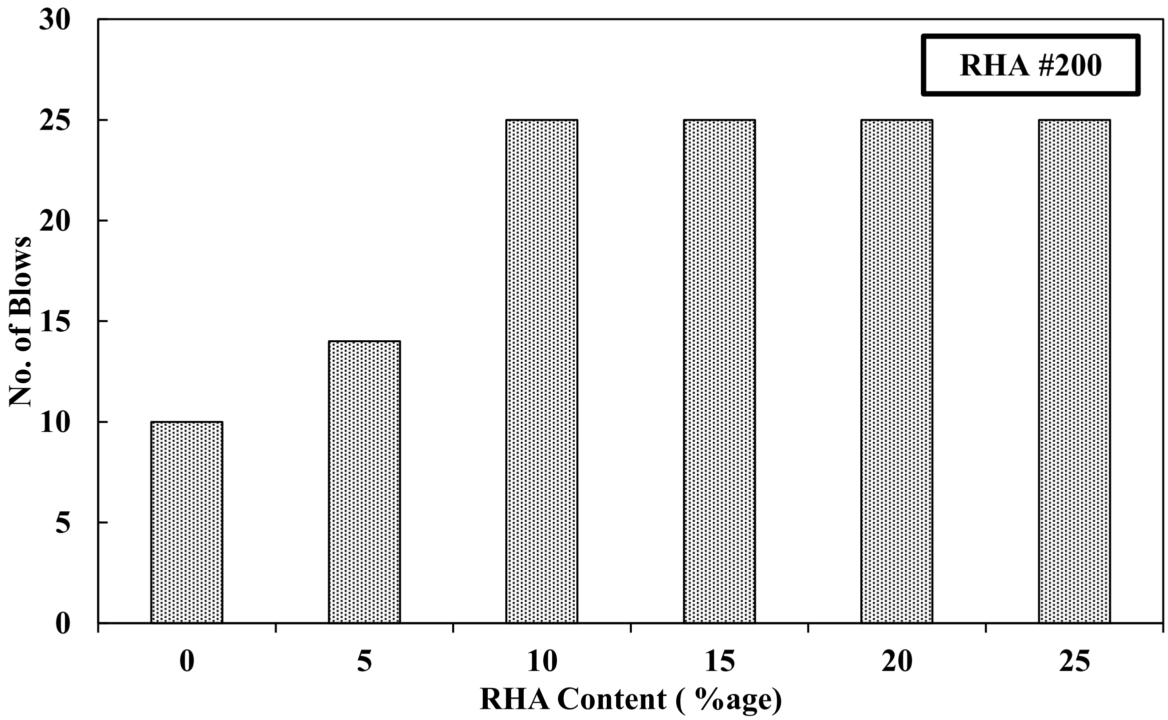
Figure 4(b) shows similar results to Figure 4(a). An important thing to note here is that at the same percentage of replacement by CBP (Sieve #200 Passing) as of CBP (Sieve #100 Passing), the total blows needed to fully cover the area of the base of the flow table was a greater number of blows were required than in the case of CBP (Sieve #100 Passing). It is important to note that for a fixed w/b ratio, the workability of finer particles is less than the workability of their counterparts.



(a) No. of blows of flow table against different percentages of CBP1

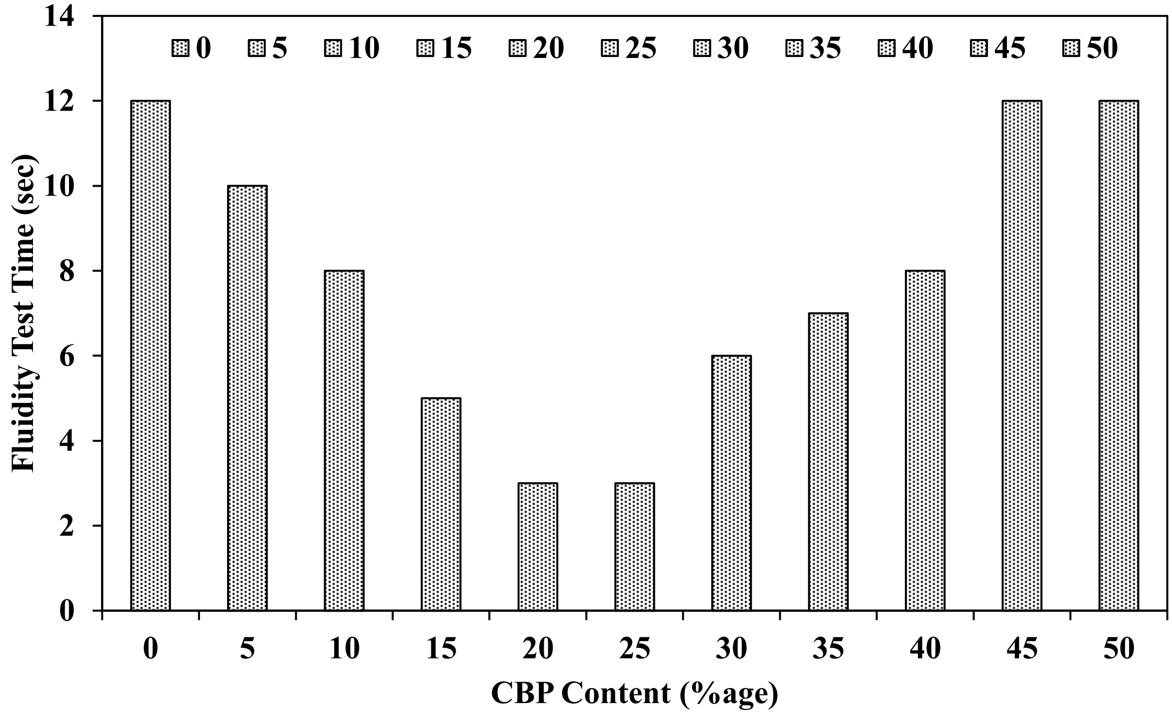


(b) No. of blows of flow table against different percentages of CBP2

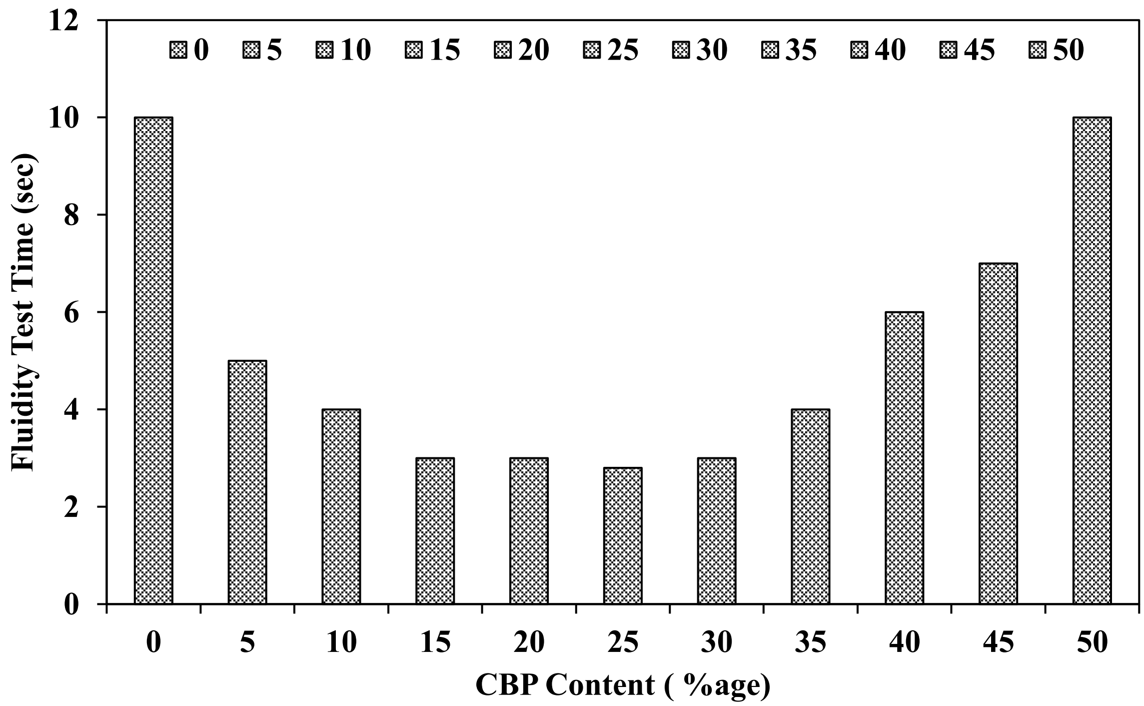


(c) No. of blows of flow table against different percentages of RHA

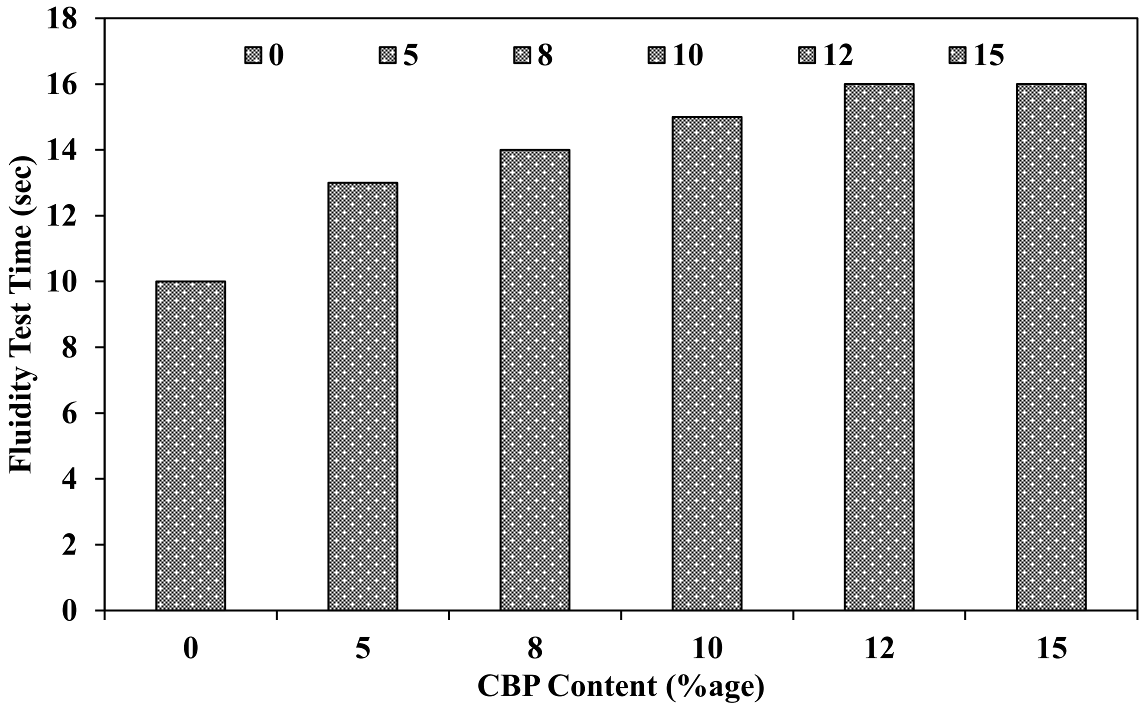
Figure 4: Flow table test showing workability of mortar pastes at different percentages of CBP1, CBP2, and RHA



a) Fluidity test for CBP (Sieve #100 Passing)



b) Fluidity test for CBP (Sieve #200 Passing)



c) Fluidity test for RHA (Sieve #200)

Figure 5: Fluidity test for different dosages of CBP (#100 & #200) & RHA (#200) with Cement

Fluidity Test:

The test was performed following (ASTM C939, 2016). Figure 5 (a) shows how the workability of cement paste changes over time when small volumes of Ultrafine brick powder (passed through sieve #100) are added. It has been shown that replacing cement by 0 to 25% reduces flow time; however, replacing cement by 25% to 50% brick powder content increases cement paste flow time. The following explains why:

Brick powder serves as SCM for lower replacement percentages (0% to 25%). SCMs often have smaller particle sizes and can fill in spaces left by missing cement, increasing the cementitious matrix's packing density. The cement paste becomes thicker and less fluid as a result of the improved packing, which might shorten the cement paste's flow time. Brick powder may also boost hydration reactions, which can speed up the cement paste's setting process and cut down on flow time. As you increase the brick powder replacement beyond 25%, several factors come into play:

Brick powder particles, compared to cement particles, are often coarser and more asymmetrical in shape. This may prevent particles from packing tightly within the paste, increasing porosity and decreasing packing density. As a result, the cement paste loses density and fluidity, lengthening the flow time.

Reduced Cement Content: When the replacement % is larger, less cement is really present in the mixture. Concrete's main binding component is cement, and a considerable decrease in cement content can weaken the structure as a whole, increasing the likelihood that it will flow and deform when under load. The flow time may go up as a result of this.

Modified Chemical interactions: Chemical processes involving the brick powder and other components of the liquid may have variable kinetics with greater replacement percentages. This may have an impact on the cement paste's rheological characteristics and setting time, lengthening the duration of flow. The findings show that increasing the rate of waste brick powder causes a modest decrease in flow time. However, the flow time increases at a 20% w/w substitution rate. At a 20% cement replacement with brick waste powder, water absorption by the powder reduces the mixture's workability (Si-Ahmed & Kenai, 2020).
Similar results were obtained when cement paste was mixed with ultrafine brick powder (passed through sieve #200) as shown in Figure 5 (b), and a flow cone test was conducted. More water is needed to produce brick powder, which reduces its workability and lengthens the time cement paste takes to flow. Along with altering the cement mix, various amounts of RHA were used. In contrast to previous replacements such as CBP, RHA replacements demonstrated that the flow time of cement paste increased with steadily increasing RHA dose, as illustrated in Figure 5 (c). Higher RHA levels in grout increase Marsh cone flow time, but changes in water-to-binder ratio have minimal effect (Celik & Canakci, 2015).

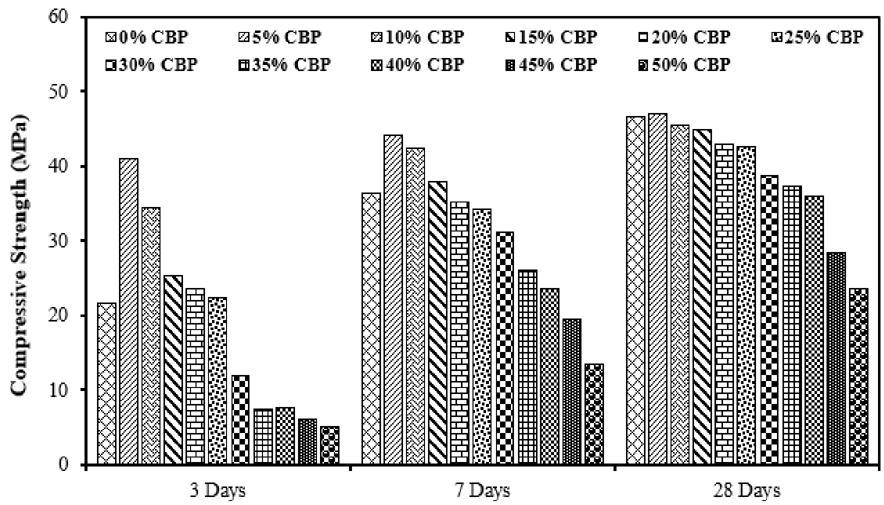
The rise in flow time and drop in workability is attributed to RHA absorbing more water than cement. The presence of voids and channels in RHA's amorphous structure leads to a high surface area. Consequently, the high surface area causes higher water absorption (Pansini, 1996). A higher paste content reduces grout fluidity by increasing its plasticity and cohesiveness (Şahmaran et al., 2006; Yahia et al., 2005).

3.4 Compression Test:

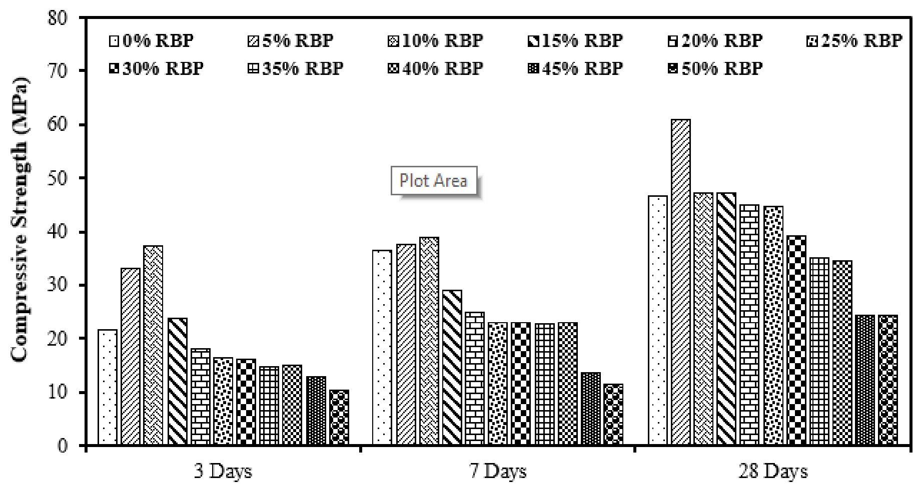
Figure 6 (a) illustrates the compressive strength of CBP passing sieve #100 of different percentage (%) dosages at 3,7, and 28 days. At 3 days, no reduction of compressive Strength was observed by varying CBP percentage up to 25% in cement. There is a large increase in compressive strength at 3 days up to 25% replacement. By referring to the control paste, for replacements of 5, 10, 15, 20, and 25%, the percentage increase in compressive strength was 90.13, 59.85, 17.52, 9.32, and 4.13 MPa, respectively. At 7 days, no reduction of compressive strength was detected with CBP replacing cement at levels up to 15%. With respect to the to the control paste for replacement, ranging 5, 10, 15 percent increase in compressive strength was 21.51, 16.53, and 4.15 MPa. At 28 days no reduction in strength for only 5% replacement. Increase in compressive strength was 1.20% for 5% substitution of cement with brick powder. A Percentage Reduction in compressive strength was observed as 2.13% for 10% replacement of cement with CBP, and it increases to 49.41% with an increase in CBP from 10 to 50% by an interval of 5% in cement. This reduction in compressive strength at 28 days was attributed to the less pozzolanic behavior of CBP. The data indicate that compressive strength declines as CBP replacement surpasses 5%, across different ages.

For a 5% substitution of cement by CBP, compressive strength increases with age. For 10 and 15% substitution of cement, compressive strength increases up to 7 days but decreases from 7 days to 28 days. Rise in compressive strength for 10 and 15% up to 7 days may be governed by the filling effect (Shao et al., 2019a). Later on, compressive strength of partially replaced cement cubes becomes less than standard mix as a result of the slow pozzolanic reaction of CBP. Lower in compressive strength was due to the slow pozzolanic reaction of CBP, which requires a longer period for complete reaction (Sinkhonde et al., 2021). From previous studies, it has been seen that the pozzolanic behavior of CBP is slow, and it increases with age (Bediako et al., 2016; Lin et al., 2010b; Lothenbach et al., 2011). The dilution effect was another reason for the drop in compressive strength as CBP content rises. With a fixed water-to-cementitious materials ratio, increasing CBP raises the effective water-to-cement ratio due to dilution, leading to a decrease in compressive strength (Ge et al., 2015b). The effect is more likely to occur when CBP has a larger size. Strength declined when cement was partially substituted with CBP, independent of particle size. The decrease became more pronounced as the replacement level and particle size increased. The impact is particularly significant within the first 28 days (Ge et al., 2015b).

Figure 6 (b) demonstrates the compressive Strength of CBP passing sieve #200 of different percentage (%) dosages at 3,7, and 28 days. Referring to the control mixture, no reduction in compressive strength was observed when the percentage of cement replaced by CBP is increased up to 15%. Compressive strength of partially replaced cement cubes increased 54.01%,72.83%, and 10.25% for 5,10, and 15% replacements of cement with CBP. Compressive strength of Cubes decreases when the Replacement percentage increases from 15% to 50% with an interval of 5. The highest reduction in compressive strength was noted with a substitution of 50% cement by CBP, which was 51.78% with respect to the control mixture. Other studies also report the same behavior as the percentage of cement replacement with CBP increases, Compressive.



a) Compressive strength of CBP passing sieve #100 at different ages



b) Compressive strength of CBP passing sieve #200 at different ages

Figure 6: Compressive Strength of CBP of different fineness

strength decreases (Heidari & Hasanpour, 2013). The 7-day compressive strength increased with CBP replacement up to 10%, beyond which a progressive decline was observed as the substitution level rose to 50%. The percentage increase in compressive strength for 5% and 10% was calculated as 3.6% and 6.85%. 68.7% degradation in compressive strength of the partially replaced cement cube was observed at 50%.

At 28 days, results showed that compressive strength was increased up to 15% cement replacement with CBP, then it decreased gradually up to 25%, and continued to decrease till 50% replacement. Percentage increase in compressive Strength for 5%,10%, and 15% was recorded as 31.2%, 1.2%, and 1.2%. Optimum increase was observed for 5% replacement of cement with CBP, with a value of 31.2%. The highest reduction was observed at 50% replacement, which was 47.4%. The degradation in compressive strength is due to the slow pozzolanic reaction of CBP with time. The rise in compressive strength was due to to fineness of CBP, which gives well packing in the early days, so compressive strength increases. Another reason for the increasing compressive strength is the less dilution effect because of fineness and a lower percentage of CBP in cement. Causes for reduction in compressive strength of partially replaced cubes may Dilution effect. No doubt dilution effect decreases with an increase in fineness, but it also depends on the percentage of replaced materials. Another reason may slow the pozzolanic reaction of CBP (Shao et al., 2019b; Sun et al., 2019).

Comparing the results of CBP for two different finenesses. It has been proved that compressive Strength increases with an increase in the fineness of CBP. Concerning control mixture, Compressive Strength of CBP passing sieve#100 increases up to 5% when used as a partial replacement of cement. Alternatively, referring to the same control mixture, compressive strength of CBP passing sieve #200 increases up to 15% when used as a partial substitution of cement. By comparing results for two different fineness (passing#100 and passing#200), An increase in CBP fineness corresponds to improved pozzolanic activity. With an increase in fineness from #100 to #200, replacement up to 15% gives satisfactory results of compressive strengths. The reason is that the increase in the fineness of CBP reactivity rate of particles is also a dilution effect, because of higher surface area of particles. Being a porous material, brick is absorbent of water.

Figure 7 depicts the compressive strength variation in cement due to RHA inclusion when partially replaced with RHA (5,8,10,12,15%) at various ages. In comparison to the control mixture, at 3-day compressive strength, partially substituted cement cubes with RHA increased by up to 12%. At 5% replacement, compressive strength increased by 48.8%. for 8% replacement, the percentage increase in compressive strength was 50.4%; similarly, 51.2% and 22.2% increases in compressive strength were obtained for 10 and 12% replacement. At 15% replacement, compressive strength was dropped by 39.6%.

Related to the control mixture, at 7-day strength increases up to 10% when cement was replaced with RHA. For 12 and 15% replacements decline in strength was observed. Percentage increase in strength for 5,8, and 10% was 19.7, 22.4, and 27.4 %, as well as dropped in compressive strength for the rest of the two replacements (12, 15) % was 15.4% and 51.8%.

At 28 days, the compressive strength of partially replaced cement cubes rises in comparison to the control mixture when RHA is replaced at varied percentages. The results reveal that the compressive strength of partially replaced cubes increases as the proportion of RHA increases, up to 12% replacement. The percentage rise in compressive strength at 28 days for 5, 8, 10, and 12% was 0.82%, 3.5%, 23.6%, and 1.59%, respectively. A 12% replacement resulted in an optimal compressive strength of 57.71 MPa. In contrast, a loss in compressive strength of 11.8% was seen when 15% of the cement was replaced with RHA.

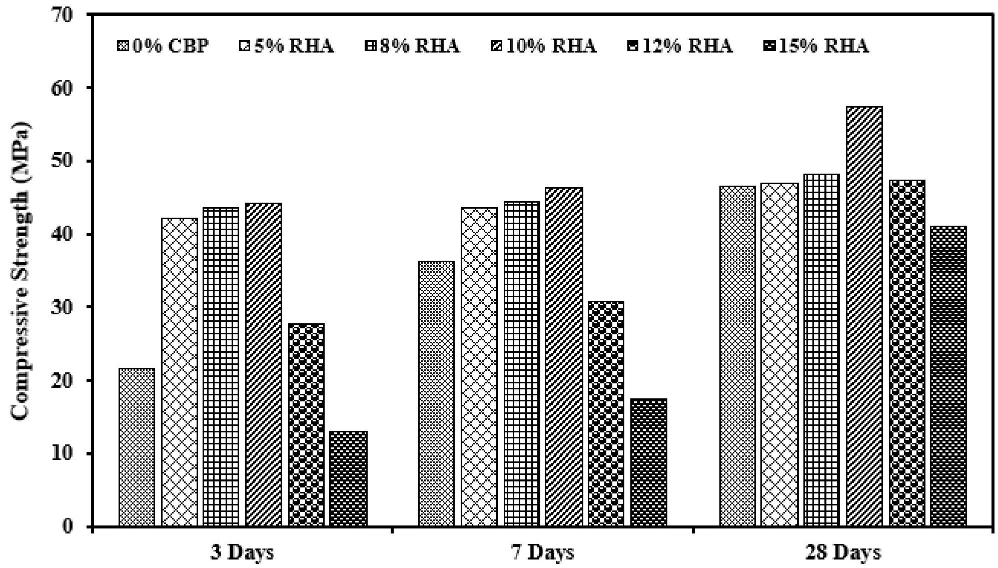


Figure 7: Compressive strength of partially replaced cement cubes by Rice Husk Ash passing sieve #200 at different ages.

Increase in compressive strength of partially replaced cubes is due to hydration of cement, filling effect, and pozzolanic reaction between silica and calcium hydroxide (Kizhakkumodom Venkatanarayanan & Rangaraju, 2015; Sata et al., 2012). The findings demonstrate that compressive strength initially increases and then decreases as the content of RHA continues to rise. This observed pattern results from the specific surface area of RHA exceeds that of cement, thereby enabling a greater capacity for interaction with calcium hydroxide and water (Zunino & Lopez, 2017). The rapid progression of the pozzolanic reaction contributes to an augmented formation of C-S-H gel, thereby enhancing the densification of the matrix and the compressive strength (Van et al., 2013). As the concentration of RHA increases to 15%, the compressive strength achieved through the pozzolanic reaction of RHA fails to adequately offset the decline in compressive educed strength resulting from lower cement dosage. This ultimately results in reduced compressive strength at higher levels of RHA content.

Conclusions

The results and analysis presented above lead to the following conclusions:

1. Ultrafine CBP and RHA are suitable partial cement substitutes in mortar composites.
2. Finer CBP particles passing the ASTM sieve #200 exhibited higher pozzolanic activity and improved strength performance.
3. Optimal replacement levels were identified at 5–15%, beyond which strength and workability declined due to dilution and higher porosity.

4. The incorporation of CBP and RHA increased the initial and final setting times, offering extended workability periods beneficial for construction.
5. The surface area and porous structure of RHA contributed to higher water demand and improved matrix densification at moderate replacement levels.
6. A significant reduction in cement usage was achieved without compromising structural performance, contributing to sustainable construction practices.
7. The recycling of construction and agricultural residues in cementitious composites reduces environmental impact and supports circular economy goals.

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