Effects of CO_2 sequestrated recycled brick powder on cement mortar properties

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Abstract. The increasing impact on environment due to the mining of river beds for the use of natural river sand as fine aggregate in mortar/concrete demands for sustainable methods. Hence, in this present study to reduce the use of natural river sand in mortar/concrete, a sustainable alternative method was investigated. This method involves the use of Recycled Brick Powder (RBP) as an alternative to river sand in cement mortar. In this present study, CO_2 sequestration method was employed on RBP and was used as a partial replacement to river sand in cement mortar. Recycled Brick Powder (RBP), which was obtained by crushing the construction demolition waste, was carbonated at various levels (0%, 10% and 20%) of CO_2 concentration in an accelerated carbonation chamber. This CO_2 sequestrated RBP was replaced at 0%, 25% and 50% by weight of that of natural river sand. Flow table test was conducted to determine the consistency of the cement mortar mixes. The compressive strength was determined at the ages of 1, 3, 7 and 28 days of curing. From the obtained results, it was observed that the increase of RBP percentage tends to reduce the consistency of cement mortar and the compressive strength. From the compressive strength test results, it was found that CO_2 sequestration had positive effect on both the consistency and compressive strength of cement mortar containing RBP. An increase in compressive strength of about 4% was observed with carbonated RBP. This research confirms that CO_2 sequestered RBP can be used as a low-carbon eco-friendly sustainable fine aggregate that helps in carbon reduction and preservation of natural resources.

1 Introduction

Concrete is the most popular construction material in the world, and it is produced in large proportions of over 30 billion tons in a year. Its power and resilience render it as an essential component, but at the same time nearly 786 kg of CO_2 is released per ton of cement production, which posses a significant problem to the environment [1, 2].

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The construction and demolition waste being generated in huge quantities requires safe disposing or using in a sustainable manner [3]. One such sustainable method is of using this construction and demolition waste in the production of concrete by way of replacement to natural fine and/or coarse aggregates. Hence, in this present study the Recycled Brick Powder (RBP), which is obtained from the construction and demolition waste, is considered and studied for possibility of potential replacement to natural river sand as fine aggregate [4].

Cement production, which results in CO_2 emissions, also require potential solutions for a sustainable cement and concrete. One such potential is offered by the CO_2 sequestration method, which is one of the promising methods of curbing this effect [5]. This CO_2 sequestration method involves the reaction of carbon dioxide with the hydration products of cement to make stable calcium carbonate ($CaCO_3$). Besides decreasing emissions, it can also enhance durability by refining the pore structure and densifying the matrix [6, 7].

The Recycled Brick Powder (RBP) obtained from the construction and demolition waste containing amorphous silica and alumina, is investigated for its potentiality as a substitute for natural river sand in cement mortars. According to the recent studies, CO_2-treated RBP can also be used to increase the strength and the carbon storage capacity [8, 9]. Thus it is understood that there is a significant need to study the possibility of use of recycled brick powder as a potential substitute to natural river sand. This present study will examine the consistency and strength of the cement mortar that uses carbonated RBP with the view of solving not only the issue of environmental concerns, but also the engineering demands for sustainable buildings.

1.1 Significance of the work

The present study integrates two essential sustainability measures viz., the CO_2 sequestration of RBP and the use of carbonated RBP as replacement to natural fine aggregate i.e. river sand. This study combats the emission of CO_2 in the atmosphere and the depletion of natural resources by utilizing the CO_2 treated Recycled Brick Powder (RBP) in the place of natural river sand partially. This not only converts construction waste to a value-added material but also makes concrete become a useful carbon sink.

In addition, analysis of the fresh (consistency) and hardened (compressive strength) characteristics of carbonated RBP will give valuable data on its practical application in construction. Its findings can be used to develop low-carbon and resource-efficient concretes that comply with current performance-based requirements, which will help to create more sustainable infrastructure systems.

2 Materials and Methods

2.1 Materials

2.1.1 Cement

This study used ordinary Portland Cement (OPC) of 53 Grade confirming to the IS: 269 [10] requirements. The specific gravity value is given in Table 1.

2.1.2 Fine Aggregate

Three types of fine aggregate were used in this study viz., firstly Ennore sand, which is a standard sand confirming to the specifications of IS: 650 [11]. Secondly, natural river sand is used as reference or control sand confirming to the specifications of IS: 383 [12]. Thirdly, RBP was used as replacement to natural river sand at various replacement levels (25% and 50%). Both the natural river sand and the recycled brick powder confirms to Zone-II and Zone-III respectively as per the specifications of IS: 383 [12]. The specific gravity values of different fine aggregates were given in Table 1.

Table 1. Specific gravity of materials

S.No.	Material	Specific Gravity
1	Cement (OPC 53 grade)	3.15
2	Natural river sand	2.36
3	Ennore sand	2.48
4	Recycled Brick Powder (RBP)	2.05

2.1.3 Water

Potable water confirming to IS: 456 [13] requirements was used in this study.

2.2 Methods

2.2.1 Production of recycled brick powder

The Recycled Brick Powder (RBP) was obtained from the construction and demolition waste. Firstly, the waste and broken bricks were separated from the construction and demolition waste and then the bricks were crushed in a laboratory type jaw crusher. The obtained brick powder was sieved though 4.75 mm IS sieve and was used as fine aggregate.

2.2.2 Carbonation of recycled brick powder

The obtained RBP was carbonated using CO_2 sequestration method. For this carbonation technique, the RBP was subjected to various levels of CO_2 concentration namely, 0%, 10% and 20% under a relative humidity of 65% and a temperature of 35^0C in an accelerated carbonation chamber. The optimum conditions for carbonation method i.e. CO_2 concentration, duration of exposure, temperature and humidity were derived from the literature [8, 9].

2.2.3 Mix Proportions

In this study, the mortar mixtures were made in cement to fine aggregate ratio of 1:6 by weight, which is a standard ratio when testing the performance of alternative fine aggregates according to the specifications of IS: 2250 [14]. Twelve mortar mixes were planned to test the influence of non-carbonated and CO_2-sequestrated (RBP) as a partial substitute to natural river sand.

The water-cement ratio for cement mortar mixes was determined as per the guidelines mentioned in IS: 2250 [14]. This was obtained as 0.70. The details of the various mixes were presented in Table 2. From the preliminary experimental trails when the replacement of RBP exceeded 50%, the mortar mixes failed to achieve workability. Hence, the percentage replacement of RBP was limited to 50% based on the preliminary trails.

2.2.4 Consistency

The flow table test was performed on the mortar mixes to determine the consistency as per the standard procedure given in IS: 2250 [14] and IS: 4031 (Part-7) [15]. From this test, the consistency of the mortars was determined.

2.2.5 Compressive strength

Standard guidelines mentioned in IS: 2250 [14] were considered to determine the compressive strength of the mortar specimens. Each mix was cast into cubes of size 50 mm and cured under controlled conditions and then tested at the ages 1, 3, 7 and 28 days. Failure loads were recorded and compressive strength was thus derived. A standard uniform loading rate of 2 N/mm^2 to 6 N/mm^2 was adopted as per IS: 2250 [14]. For each age, three specimens were cast, tested and the average result was reported as the compressive strength.

Table 2. Description of various mixes

Mix ID	Description	Cement : Fine Aggregate (by weight)	Water-cement ratio	RBP Replacement (%)	Carbonation (%)
M1	Control Mix (Ennore sand)	1 : 6	0.70	0	-
M2	Control Mix (Natural river sand)	1 : 6	0.70	0	-
M3	Non-Carbonated RBP + Natural river sand	1 : 6	0.70	25	0
M4	Non-Carbonated RBP + Natural river sand	1 : 6	0.70	50	0
M5	Carbonated RBP + Natural river sand	1 : 6	0.70	25	10
M6	Carbonated RBP + Natural river sand	1 : 6	0.70	50	10
M7	Carbonated RBP + Natural river sand	1 : 6	0.70	25	20
M8	Carbonated RBP + Natural river sand	1 : 6	0.70	50	20

3 Results and discussions

3.1 Effect of non-carbonated RBP on consistency

The fresh property i.e. consistency of the mortar was determined using the flow table test as per the specifications of IS: 2250 [14]. This flow table test was conducted on the mortar mixes containing Ennore sand (Mix: M1), natural river sand (Mix: M2), 25% RBP (Mix: M3) and 50% RBP (Mix: M4). These results were presented in Fig. 1. From the Fig. 1, it can be observed that the consistency of the mortar mixes M1 and M2 were as per the requirements of IS: 2250 [20] i.e. greater than 110%. However, when the fine aggregate was replaced with RBP at 25% (Mix M3) and 50% (Mix M4) replacement levels, the consistency was reduced to 100% and 75% respectively. The Table 3 presents a typical comparison and percentage change of consistency for various mixes (M1, M2, M3 and M4). From this table, it is understood that the M3 mix (i.e. 25% RBP) had shown about 9.1% reduction in the consistency whereas M4 mix (i.e. 50% RBP) had shown 31.8% reduction in consistency. From this, it is clearly understood that higher the replacement level of RBP, higher is the reduction in consistency. The primary reason can be attributed to the highly porous nature of RBP particles causing absorption of water leading to reduction in consistency of the mortar. When compared to 50% RBP replacement level, the 25% RBP replacement level had shown acceptable consistency of about 100%.

3.2 Effect of carbonated RBP on consistency

CO_2 sequestration was employed on RBP at concentrations of 10% and 20% CO_2. This CO_2 sequestrated RBP was used at 25% and 50% replacement levels of that of natural river sand. The flow table test was conducted on the carbonated RBP mixes and the results were presented in Fig. 2. From the Fig. 2, it can be noted that the CO_2 sequestration technique had improved the consistency of the mortar mixes. The higher the CO_2 concentration, higher was the increase in consistency of the mortar mixes. When 10% CO_2 concentration was employed, the 25% RBP mix (Mix: M5) has resulted in 102% consistency (increased from 100%) whereas 50% RBP mix (Mix: M6) consistency was improved to 80% (increased from 75%). These were further increased to 110% and 92% when the CO_2 concentration was increased to 20%. The Table 4 presents a typical comparison and percentage change of consistency for various mixes (M3, M4, M5, M6, M7 and M8). From Table 2, it is observed that the M5 mix (i.e. 25% RBP + 10% CO_2) had shown about 2.0% increase in the consistency whereas M7 mix (i.e. 25% RBP + 20% CO_2) had shown 10.0% increase in consistency when compared to non-carbonated RBP mix. These percentage increases for 50% RBP were 6.7% (M6 mix) and 22.7% (M8 mix) respectively for 10% CO_2 and 20% CO_2 when compared to non-carbonated RBP mix (M4). From this, it is clearly understood that higher the CO_2 concentration, higher is the increase in consistency. The CO_2 sequestration converted the hydration products of cement in the RBP to stable calcium carbonate ($CaCO_3$). This resulted in the densification of particle surface and leading to reduction of water absorption. This had greatly improved the consistency of the mortar mixes. Thus CO_2 sequestration technique was found to greatly increase the workability and the effect was more pronounced with increase in CO_2 content, which implies that the CO_2 treatment reduces the negative impact of RBP on the workability. This increase has been reported and supported by the literature [8-9]. The 20% carbonated RBP at 25% replacement level had shown similar results as that of the Ennore sand. Also, the results were slightly better than natural river sand and hence can be used as potential substitute to natural river sand in mortars.

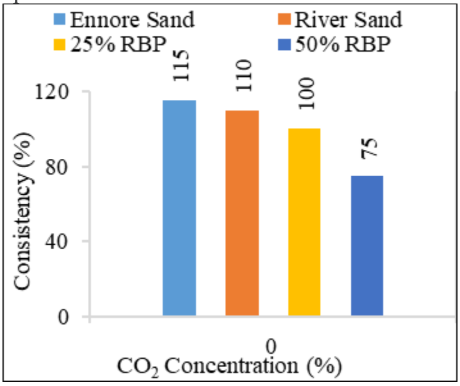

Fig. 1. Effect of non-carbonated RBP on consistency of mortar mixes

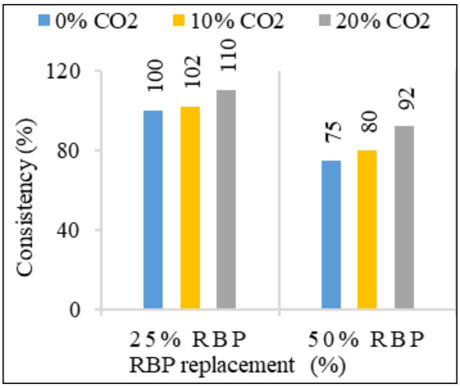

Fig. 2. Effect of CO_2 sequestration on consistency of mortar mixes

Table 3. Percentage change in consistency for non-carbonated RBP mixes

Mix ID	Consistency (%)
M1 (Ennore sand)	115
M2 (Natural river sand)	110
M3 (25% RBP)	100
% change in consistency for M3 compared to M2	**(-) 9.1%**
M4 (50% RBP)	75
% change in consistency for M4 compared to M2	**(-) 31.8%**

Table 4. Percentage change in consistency for carbonated RBP mixes

Mix ID	Consistency (%)
M3 (25% RBP non-carbonated)	100
M5 (25% RBP + 10% CO_2)	102
% change in consistency for M5 compared to M3	**(+) 2%**
M7 (25% RBP + 20% CO_2)	110
% change in consistency for M7 compared to M3	**(+) 10.0%**
M4 (50% RBP non-carbonated)	75
M6 (50% RBP + 10% CO_2)	80
% change in consistency for M6 compared to M4	**(+) 6.7%**
M8 (50% RBP + 20% CO_2)	92
% change in consistency for M8 compared to M4	**(+) 22.7%**

3.3 Effect of non-carbonated RBP on compressive strength

The compressive strength was determined on cube specimens of size 50 mm as per the guidelines of IS: 2250 [14]. The compressive strength was determined after curing ages of 1, 3, 7 and 28 days. At each age, three specimens were cast, tested and the average result of compressive strength was reported. The results of the compressive strength were presented in Figures 3, 4, 5 and 6 for curing ages of 1, 3, 7 and 28 days respectively. From these figures, the mortar mix containing Ennore sand (Mix: M1) had shown higher compressive strength results at all ages. At 28 days of age, the M1 mix had shown highest compressive strength of 16.0 MPa. The traditionally used fine aggregate i.e. natural river sand mortar mix (Mix: M2) had shown lower results when compared to mix M1. The mix M2 had shown a compressive strength of 12.4 MPa at 28 days. When the natural river sand was replaced with RBP at 25% (Mix: M3) the compressive strength at 28 days was increased to 14.5 MPa. This can be attributed to the absorption of water by the RBP leading to higher compressive strength. However, the compressive strength was reduced to 13.5 MPa when the RBP replacement was further increased to 50%. This similar pattern was observed for all other ages of 1, 3 and 7 days. The percentage change in compressive strength results were presented in Table 5. From this table it is understood that the percentage increase in 28-day compressive strength for 25% RBP replacement level was about 16.9% and was reduced to 8.9% for 50% RBP. This suggests that a replacement level of 25% RBP was an optimum percentage that offers a considerable increase in strength. Thus, a 25% replacement of RBP offers sustainable construction by way of utilizing waste.

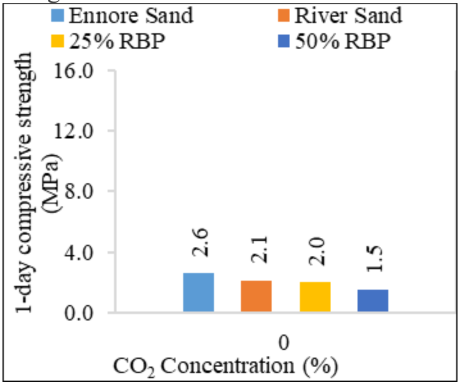

Fig. 3. Influence of non-carbonated RBP on 1-day compressive strength

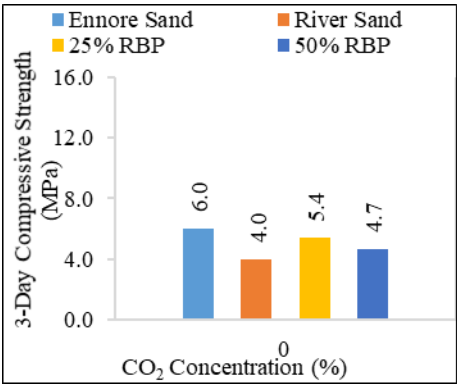

Fig. 4. Influence of non-carbonated RBP on 3-day compressive strength

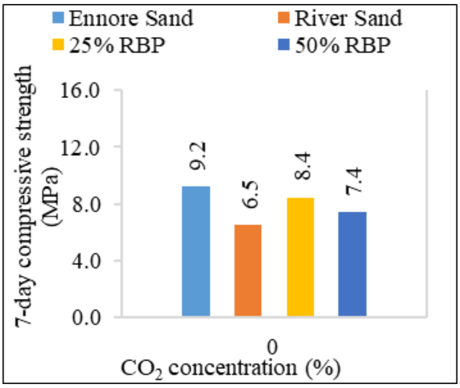

Fig. 5. Influence of non-carbonated RBP on 7-day compressive strength

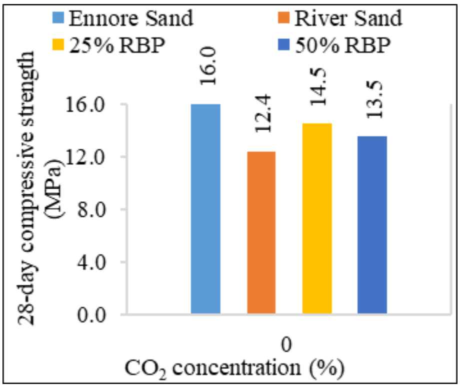

Fig. 6. Influence of non-carbonated RBP on 28-day compressive strength

Table 5. Percentage change in compressive strength for non-carbonated RBP mixes

Mix ID	28-day compressive strength (MPa)
M2 (Natural river sand)	12.4
M3 (25% RBP)	14.5
% change in compressive strength of M3 mix compared to M2 mix	**(+) 16.9%**
M4 (50% RBP)	13.5
% change in compressive strength of M4 mix compared to M2 mix	**(+) 8.9%**

3.4 Effect of carbonated RBP on compressive strength

The CO_2 sequestration technique was employed on RBP raw material at different concentrations of 10% and 20%. This sequestration was carried out for a time period of 4 hours at temperature of 35°C and relative humidity of 65% in an accelerated carbonation chamber. The results of the compressive strength test were compared for mixes M3, M4, M5, M6, M7 & M8 and were presented in the Figures 7, 8, 9, 10 for ages 1, 3, 7 and 28 days respectively. From these figures, it is observed that when the carbonated RBP was replaced at 25% with natural river sand, the 28-day compressive strength was increased to 15.1 MPa for 10% CO_2 concentration (Mix: M5) and 15.6 MPa for 20% concentration (Mix: M7) versus 14.5 MPa for non-carbonated RBP mix (Mix: M3). Similarly, for 50% replacement level of RBP, the 28-day compressive strength was increased to 14.0 MPa for 10% CO_2 concentration (Mix: M6) and 14.6 MPa for 20% concentration (Mix: M8) versus 13.5 MPa for non-carbonated RBP mix (Mix: M4). This similar pattern was observed for all other ages of 1, 3 and 7 days. The Table 4 presents a typical comparison of the percentage increase in compressive strength of carbonated RBP mixes. From the Table 6 it is clear that the 28-day compressive strength for 25% RBP mix increased by 4.1% and 3.3% when 10% and 20% CO_2 was employed respectively when compared to non-carbonated RBP mix. These percentage increases were 3.7% and 4.3% respectively for 10% and 20% CO_2. The reason can be attributed to the improvement in pore structure of RBP due to CO_2 sequestration thereby the formation of stable calcium carbonate. Also, the improvement in the ITZ can be attributed to the improvement in the mortar properties. The same phenomenon has also been reported and supported by the literature [8-9]. From this, it can be concluded that the 10% CO_2 sequestration had yielded in better compressive strength results. Through this findings, it can be suggested for use of this carbonated recycled brick powder as an potential alternative in view of sustainable and responsible consumption of natural resources.

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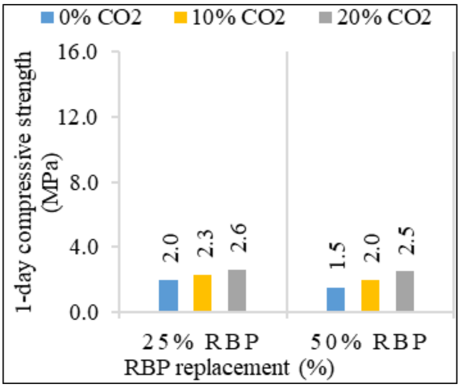

Fig. 7. Influence of CO_2 sequestration on 1-day compressive strength of RBP mortar mixes

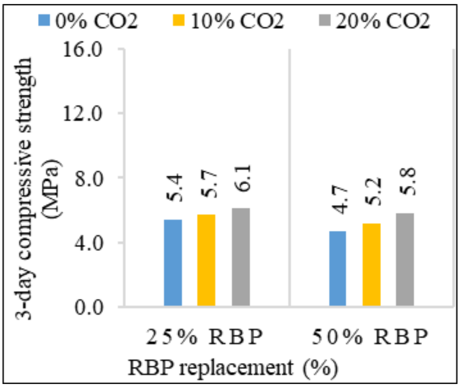

Fig. 8. Influence of CO_2 sequestration on 3-day compressive strength of RBP mortar mixes

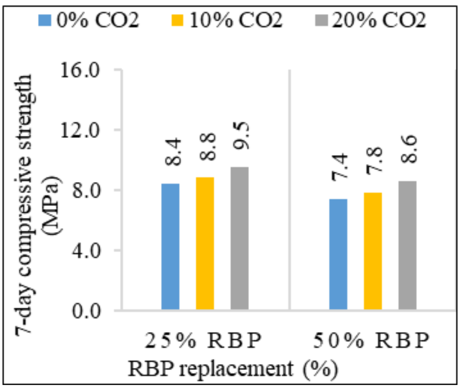

Fig. 9. Influence of CO_2 sequestration on 7-day compressive strength of RBP mortar mixes

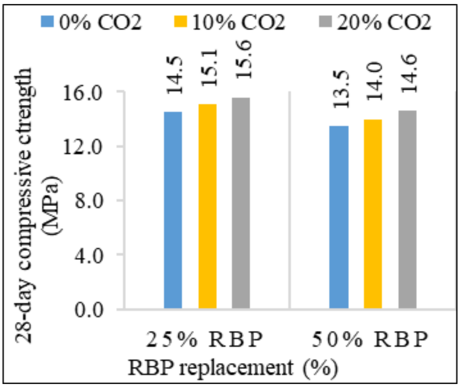

Fig. 10. Influence of CO_2 sequestration on 28-day compressive strength of RBP mortar mixes

Table 6. Percentage change in compressive strength for carbonated RBP mixes

CO_2 (%)	28-day compressive strength (MPa)	
	25% RBP	**50% RBP**
0% CO_2	14.5 (Mix: **M3**)	13.5 (Mix: **M4**)
10% CO_2	15.1 (Mix: **M5**)	14.0 (Mix: **M6**)
% change in compressive strength for 10% CO_2 over 0% CO_2 (Mix M5 over Mix M3)	**(+) 4.1%**	**(+) 3.7%**
20% CO_2	15.6 (Mix: **M7**)	14.6 (Mix: **M8**)
% change in compressive strength for 20% CO_2 over 10% CO_2 (Mix M7 over Mix M3)	**(+) 3.3%**	**(+) 4.3%**

4 Conclusions

From the detailed study on feasibility of using RBP as partial substitute for natural river sand in cement mortars, the following conclusions were drawn:

1. The replacement of natural river sand with RBP decreased the consistency of mortar. The control mixes exhibited high consistency of 115% (M1 mix) and 110% (M2 mix), whereas 25% RBP (M3 mix) and 50% RBP (M4 mix) had shown 100% and 75% only.
2. When CO_2 sequestration technique was employed, the consistency was improved by about 2.0% and 10.0% for 10% CO_2 (M5 mix) and 20% CO_2 (M7 mix) respectively for 25% RBP mixes. Whereas these percentages were 6.7% (M6 mix) and 22.7% (M8 mix) in case of 50% RBP mixes.
3. The compressive strength of mortar with Ennore sand (Mix: M1) and natural river sand (Mix: M2) was about 16.0 MPa and 12.4 MPa respectively. When natural river sand was replaced with 25% RBP (Mix :M3), the compressive strength was increased by 16.9% to 14.5 MPa whereas this percentage increase was 8.9% only (13.5 MPa) in case of 50% RBP (Mix: M4).
4. The CO_2 sequestration technique employed on RBP had increased the compressive strength of mortar. The compressive strength of M5 mix (25% RBP + 10% CO_2) was increased by 4.1% compared to M3 mix (25% RBP non-carbonated). Similarly, the compressive strength of M7 mix (25% RBP + 20% CO_2) was increased by 3.3% compared to M3 mix.
5. When the RBP replacement percentage was increased to 50%, the compressive strength of M6 mix (50% RBP + 10% CO_2) was increased by 3.7% compared to M4 mix (50%

RBP non-carbonated). Similarly, the compressive strength of M8 mix (50% RBP + 20% CO_2) was increased by 3.3% compared to M4 mix.

6. From this detailed experimental study, it is confirmed that CO_2 sequestration technique on RBP has improved the consistency and compressive strength of cement mortar.
7. An RBP replacement level of 25% with 20% CO_2 concentration has shown reliable results in terms of consistency and compressive strength.
8. Hence, this replacement level of 25% RBP with 20% CO_2 carbonation and is suggested.
9. The future directions of the present study shall be towards assessing the durability characteristics of the CO_2 sequestrated RBP in cement mortars and also its microstructural aspects.

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Author Contributions

The experimental work, analysis of results and the drafting of manuscript is carried out by Vaishnavi Chikine. The concept, design of experiments, analysis of data, review of manuscript is carried out by Rakesh Siempu. The concept and review of manuscript was carried out by Ilias Said.

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