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Abstract	To reduce the carbon footprint of common construction materials like mortar and concrete, previous research has focused on the combination of natural sand and gravel with cement-based materials. However, the application of porous particles such as waste red bricks, a common byproduct of the building construction, and artificial lightweight aggregates sintered from industrial sludge has been less studied. This study therefore used waste red brick sand and artificial lightweight sand instead of natural river sand to prepare mortar cube specimens for study. The study compared the effects of CO_2 curing on the engineering properties of the two mortars and their CO_2 sequestration effectiveness. The test results showed that red brick mortar had slightly better workability than lightweight sand mortar. However, in terms of compressive strength, ultrasonic pulse velocity, and water absorption, the lightweight sand mortar performed better, with higher strength and faster velocity than red brick mortar, and lower water absorption. This indicates that lightweight sand mortar is more effective in CO_2 sequestration than red brick mortar.

Keywords (separated by '-')	CO_2 Curing - Porous Aggregate - Mortar - Engineering Properties

Effect of CO_2 Curing on the Engineering Properties of Mortar Incorporating Recycled Aggregate

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Abstract. To reduce the carbon footprint of common construction materials like mortar and concrete, previous research has focused on the combination of natural sand and gravel with cement-based materials. However, the application of porous particles such as waste red bricks, a common byproduct of the building construction, and artificial lightweight aggregates sintered from industrial sludge has been less studied. This study therefore used waste red brick sand and artificial lightweight sand instead of natural river sand to prepare mortar cube specimens for study. The study compared the effects of CO_2 curing on the engineering properties of the two mortars and their CO_2 sequestration effectiveness. The test results showed that red brick mortar had slightly better workability than lightweight sand mortar. However, in terms of compressive strength, ultrasonic pulse velocity, and water absorption, the lightweight sand mortar performed better, with higher strength and faster velocity than red brick mortar, and lower water absorption. This indicates that lightweight sand mortar is more effective in CO_2 sequestration than red brick mortar.

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1 Introduction

Concrete is the most widely used construction material, mainly due to its ease of construction and low price. The strength of concrete primarily comes from the hydration reaction of cement, leading to the results that the global cement consumption continues to increase yearly [1–4]. Regarding the rise of global environmental awareness, the cement manufacturing process requires mining natural limestone rocks, which are calcined at high temperatures and then ground. This process consumes a lot of energy and emits much carbon dioxide, which is not conducive to protecting the natural environment [5–8]. Consequently, reducing the use of natural sand and gravel in concrete is an important research issue. It is worth improving the porous structure of industrial by-products and enhancing the value of porous particles in replacing natural aggregates

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[9–12]. To reduce the carbon footprint of concrete throughout its life cycle has gradually received attention.

The strength of cement mortar mainly comes from the calcium silicate hydrate (C–S–H) gel generated by the hydration reaction. However, this process also produces calcium hydroxide ($Ca(OH)_2$), which has limited strength and is unstable for durability [13, 14]. Carbon dioxide (CO_2) curing technology makes use of this point. By reacting CO_2 with $Ca(OH)_2$, stable and water-insoluble calcium carbonate ($CaCO_3$) crystals are formed [15]. The reaction process is shown in the chemical reaction formula (1):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

In addition to reacting with $Ca(OH)_2$, CO_2 can react with other cement hydrates such as C-S-H gel to further generate $CaCO_3$. These newly formed $CaCO_3$ crystals act as micro-fillers inside the material and can fill the pore structure in the cement-based materials [16]. This physical filling effect significantly improves the overall density of the material, thereby enhancing the material's mechanical properties such as compressive strength and flexural strength. From the perspective of a sustainable environment, this process can permanently sequester CO_2, the main greenhouse gas, in stable cement-based materials, achieving the goal of effective carbon sequestration and net zero emissions [15].

The common waste, red bricks and artificial lightweight aggregates in the construction industry, have many internal pores and high water absorption rates. Their strength is not as high as general natural aggregates, and their application range is limited. This porosity is considered a weakness of material performance because it will lead to a decrease in the strength of concrete [15]. However, in the environment of CO_2 curing, the high porosity inside the porous aggregate can be regarded as an advantage. High porosity provides more permeation channels for CO_2, allowing it to penetrate deep into the aggregate, thereby effectively increasing the reaction contact area between CO_2 and cement hydration products. This accelerates the carbonization reaction and increases the overall carbon sequestration amount. Using the porous structure of red bricks and lightweight aggregates as an efficient "carbon reaction carrier," the pore structure that was initially not conducive to strength is filled with strong $CaCO_3$ crystals through carbon mineralization, thereby increasing the strength and density of the porous aggregate.

Studies have shown [17–20] that porous aggregate concrete cured with CO_2 has significantly improved physical and mechanical properties, increased density, enhanced compressive and flexural strengths, and reduced porosity and water absorption. Tesovik et al. [16] pointed out that premature or prolonged "simultaneous curing carbonation" may have adverse effects. Prolonged carbon mineralization immediately after the hardening of cement-based material will lead to premature consumption of calcium ions (Ca^+) in the material. Calcium is a key element in forming C-S-H gel in the cement hydration reaction, and C-S-H gel is the primary source of early strength development in cement-based materials. The carbon mineralization will consume the calcium before forming C-S-H gel. This will result in an increase in micro porosity inside the cement-based material and a decrease in its mechanical properties. On the contrary, "post-curing carbonation" is a more ideal strategy. This method allows cementitious materials to develop enough strength through hydration reactions before CO_2 curing initially. During this period, carbon mineralization reactions can more effectively fill the remaining pores in the cementitious material, increasing its density and sequestering carbon. This curing method allows cementitious materials to reap the ad-vantages of both reactions, optimizing mechanical properties and carbon sequestration.

Based on the analysis above, this study aimed to apply CO_2 curing to red brick and lightweight sand mortars to investigate their effects on the compressive strength, ultrasonic pulse velocity, and water absorption rate of the mortars.

2 Experimental Procedures

2.1 Materials

The main materials used in this study include red brick sand, lightweight sand, cement, and CO_2. The red brick sand (Fig. 1) was crushed and screened from waste red bricks, while the lightweight sand (Fig. 2) was crushed and screened from coarse lightweight aggregate (800 grade) produced with reservoir sludge in Taiwan. The cement used was standard Portland Type I cement, its properties meet the requirements of CNS 61. Commercially available compressed CO_2 in cylinders (Fig. 3) was used. Mortar specimens were cured with CO_2 for 3 h after demolding using a custom-designed neutralization apparatus (Fig. 4). The cast specimens were then placed in water and cured until the test age for testing.

2.2 Experimental Variables and Test Methods

This study used red brick sand and lightweight sand to fully replace natural river sand. Mortar cube specimens (50 mm × 50 mm × 50 mm) were prepared using a cement: sand: water ratio of 1:2.75:0.5 (by weight). Test ages were 3, 7, and 28 days. To evaluate the effectiveness of CO_2 curing, four different mortar specimen preparation methods were designed. The specimen numbers with the descriptions are shown in Table 1.

All the tests performed in this study were carried out in accordance with relevant regulations to ensure the accuracy and repeatability of the experimental data. The relevant experimental items and methods are summarized as follows:

Basic Property Test.

Sieve Analysis. According to ASTM C33 specification, it is used to determine the size, gradation and fineness modulus (FM) of red brick sand and lightweight sand to ensure that it meets the standard requirements. The particle size distribution of both kind sands after grading adjustment is shown in Fig. 5. Their FMs are shown in Table 2.

Water Absorption and Specific Gravity. According to ASTM C128 specifications, the water absorption and specific gravity of red brick sand and lightweight sand in the state of saturated surface dry are measured, as shown in Table 2.

Fresh Mortar Properties Test. The flow of fresh mortar was measured according to the provisions of ASTM C1437 to confirm the workability of fresh mortar.

Curing Test. The curing test in ordinary water was carried out according to the provisions of ASTM C31, and the CO2 curing was carried out according to the test method of reference [20].

Hardened Mortar Property Test.

Compressive Strength. According to the ASTM C109 specification, it is used to test the strength development of mortar.

Ultrasonic Pulse Velocity. According to the ASTM C597 specification, the ultrasonic pulse velocity is used to measure the uniformity, porosity and cracks of cement-based materials, and to verify the compressive strength test results.

Water Absorption Test. According to the ASTM C1403 specification, it is used to measure the relative water absorption performance of mortar over time and estimate its internal density.

Table 1. Experimental variables.

Sample no	Description
BN	Red brick mortar cured without CO_2
BM	Red brick mortar cured with CO_2
LN	Lightweight mortar cured without CO_2
LM	Lightweight mortar cured with CO_2

Table 2. Basic properties of sands.

Material	24 h water absorption (%)	Specific gravity	FM
Red brick sand	15.4	2.17	3
Lightweight sand	24.8	1.63	2.93

Fig. 1. Red brick sand.

Fig. 2. Lightweight sand.

Fig. 3. Compressed CO_2 cylinders.

Fig. 4. Neutralization apparatus.

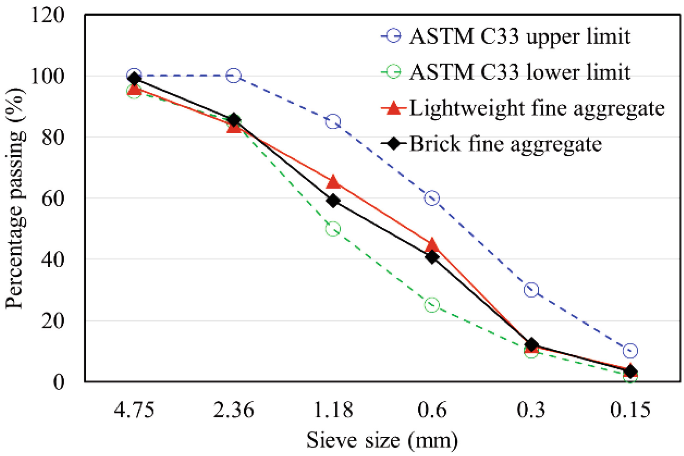

Fig. 5. Grading curve of sands.

3 Results and Discussion

3.1 Fluidity of Fresh Mortar

According to the test method of ASTM C1437, flow tests were conducted on a fluidity test bench after the mortars were mixed. The measured mortar diffusion diameters are shown in Table 3. Test results show that the flow of the red brick mortar was 107%, slightly higher than that of the 105% of the lightweight mortar. Due to the larger pore size of the red brick sand, it does not absorb mixing water as effectively as the smaller pore size of the lightweight sand. Therefore, the additional absorption from mixing water during the fresh mix stage is less pronounced than in the lightweight mortar. Consequently, the reduction of mixing water in fresh red brick mortar is less, resulting in a higher fluidity.

3.2 Compressive Strength of Mortar

The compressive strength tests was adopted for evaluating the effects of different curing conditions on the mechanical properties of mortars. Figure 6 shows the strength development of mortar at different curing ages. It shows that the compressive strength of the lightweight mortar is higher than that of the red brick mortar at with various curing methods all test ages. This is due to the inherent strength of the lightweight sand being higher than that of the red brick sand. Comparing the effects of CO_2 curing on the strength of the two mortars revealed that the compressive strength of the CO_2-cured lightweight mortar (LM) is higher than that of the unCO_2-cured lightweight mortar specimen (LN) at all ages. The strength of the LM mortar at 28 days reaches to 47.1 MPa higher than that of the LN mortar of 42.6 MPa.

Moreover, the effect of CO_2 curing on the strength of red brick mortar reveals that its strength development is similar to that of the lightweight mortar. Especially, the strength of the CO_2-cured BM mortar is higher than that of the unCO_2-cured BN mortar. This indicates that CO_2 curing can effectively improve the strength of the mortar and convert CO_2 into a solid gel that fills the pores within the mortar, achieving the end of CO_2 sequestration.

3.3 Ultrasonic Pulse Velocity of Mortars

Figure 7 shows the results of ultrasonic pulse velocity tests. The development in ultrasonic pulse velocity is similar to the compressive strength, demonstrating that CO_2 curing effectively improves mortar density, achieving the desired CO_2 sequestration effect. The speed of ultrasonic pulse propagation within mortar is positively correlated with the material's uniformity, porosity, and density. Faster pulse velocity indicates a denser material with fewer pores and cracks. Comparing the pulse velocity differences at 3 days reveals that the LN mortar has a pulse velocity of 3469 m/s, less than the LM mortar of 3856 m/s. The difference be-tween the two pulse velocities is 387 m/s, greater than the 150 m/s difference at 28 days. This indicates that CO_2 curing is more effective in improving the density of lightweight mortar at an early age (3 days). The pulse velocity development at 7 and 28 days is similar to that of mortar cured in ordinary water (the slopes of the pulse velocity curve are nearly identical), indicating that CO_2 curing has no significant effect on improving mortar density after 3 days of age. Comparing the pulse velocity measurements of red brick mortar reveals that its pulse velocity growth trend is similar to that of lightweight mortar. In addition, its pulse velocity is lower than that of lightweight sand mortar, indicating that lightweight mortar is denser than red brick mortar and can absorb more CO_2.

3.4 Water Absorption of Mortars

Table 3 shows the test results of the 24-h absorption of mortars. The water absorption of mortar cured with CO_2 (BM, LM) is lower than that of mortar not cured with CO_2 (BM, LM), and the water absorption of lightweight mortar cured or without cured with CO_2 (4.2%, 6.1%) is lower than that of red brick mortar (5.6%, 8.3%). CO_2 curing significantly affects the surface of the mortar specimens, making the mortar surface more compact and reducing internal pores, thereby decreasing the mortar's water absorption. Furthermore, the pores within lightweight sand are small and dense, making it less capable of absorbing water than red brick sand. Even after the mortar has hardened, it can continue to release water from these tiny pores, curing the interface transition zone between the aggregate and the cement paste, reducing micro-cracks and pores in the interface transition zone, and making the mortar more compact. This also contributes to the lower water absorption of lightweight mortar. This result is also corroborated by the test results showing that lightweight mortar has higher compressive strength than red brick mortar and faster ultrasonic pulse velocity than red brick mortar.

Table 3. Fresh and harden properties of mortar.

Spacemen no	Flow (%)	24 h water absorption (%)	Compressive strength (MPa)			Ultrasonic pulse velocity (m/s)		
			3 day	7 day	28 day	3 day	7 day	28 day
BN	105	8.3	22.7	26.5	35.2	3231	3374	3612
BM		5.6	26.2	31.1	37.8	3402	3493	3771
LN	107	6.1	30.1	36.7	42.6	3469	3722	3848
LM		4.2	35.9	41.7	47.1	3856	3902	3993

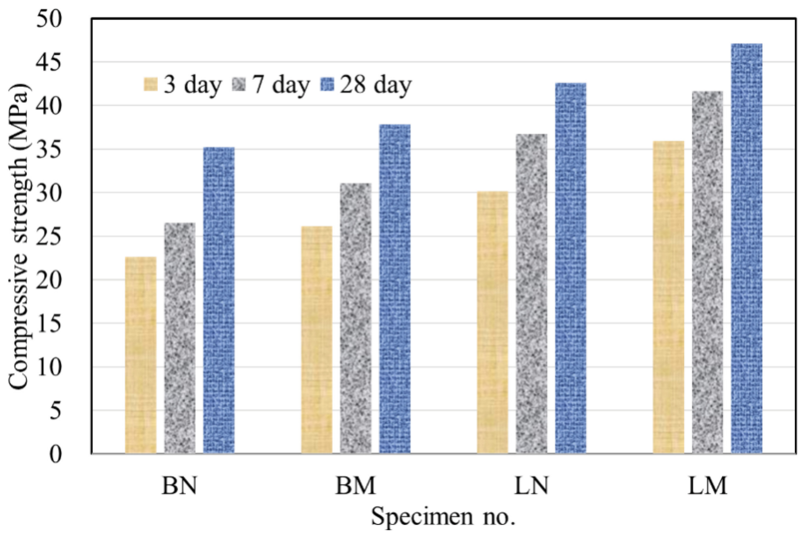

Fig. 6. Compressive strength of mortar.

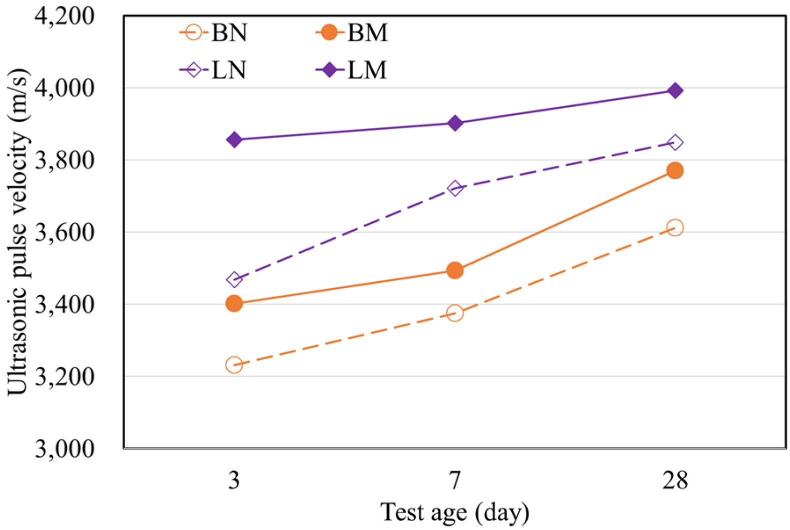

Fig. 7. Ultrasonic pulse velocity of mortar.

4 Conclusion

This study used waste red bricks and reservoir silt lightweight aggregates, both industrial byproducts, to replace natural river sand for producing mortar commonly used in construction. The effects of CO_2 curing on the properties of both mortars were investigated. The relevant test results are summarized below:

1. Flow test results indicate that the red brick mortar has slightly higher workability than the lightweight mortar. The lightweight sand absorbs water more readily than red brick sand during mortar mixing, reducing mixing water in lightweight mortar.
2. Lightweight sand inherently has higher strength than red brick sand, and the strength of mortar cured with CO_2 is higher than that of mortar without CO_2 curing. The lightweight mortar exhibits higher compressive strength than red brick mortar at all ages.
3. The ultrasonic pulse velocity measurements indicate that CO_2 curing improves the density of the mortar, with the pulse velocity being faster than that of mortar without CO_2 curing.
4. The water absorption of mortars cured with CO_2 is lower than that of mortars not cured with CO2, indicating that the surface of the CO_2-cured mortar is denser and the pores are filled with $CaCO_3$ crystals by the reaction of CO_2 and $Ca(OH)_2$.
5. Mortars with porous particles like red brick sand and lightweight sand show increased strength and mortar density after CO_2 curing, demonstrating a specific CO_2 sequestration effect.

References

1. Suhendro, B.: Toward green concrete for better sustainable environment. Procedia Eng. **95**, 305–320 (2014)

2. Zhang, Z., Angst, U., Troian, V., Guo, B., Zeng, Q.: Durability performance of concrete incorporating carbonated recycled coarse aggregates: a review. npj Mater. Sustainability **3**(27), 2025
3. Samad, S., Shah, A.: Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: a critical review. Int. J. Sustain. Built Environ. **6**(2), 663–674 (2017)
4. Althoey, F., Ansari, W.S., Sufian, M., Deifalla, A.F.: Advancements in low-carbon concrete as a construction material for the sustainable built environment. Dev. Built Environ. **16**, 100284 (2023)
5. Chaudhury, S.R., Sharma, U., Thapliyal, P.C., Singh, L.P.: Low-CO_2 emission strategies to achieve net zero target in cement sector. J. Clean. Prod. **417**, 137466 (2023)
6. Khaiyum, M.Z., Sarker, S., Kabir, G.: Evaluation of carbon emission factors in the cement industry: an emerging economy context. Sustainability **15**(21), 15407 (2023)
7. Barbhuiya, S., Das, B.B., Adak, D.: Roadmap to a net-zero carbon cement sector: strategies, innovations and policy imperatives. J. Environ. Manage. **359**, 121052 (2024)
8. Omar, A., Muthusamy, K.: Concrete industry, environment issue, and green concrete: a review. Construction **1**(2), 1–9 (2022)
9. Mi, R., Yu, T., Poon, C.S.: Feasibility of utilizing porous aggregates for carbon sequestration in concrete. Environ. Res. **228**, 115924 (2023)
10. Zhan, B., Poon, C.S., Liu, Q., Kou, S., Shi, C.: Experimental study on CO_2 curing for enhancement of recycled aggregate properties. Constr. Build. Mater. **67**(Part A), 3–7 (2014)
11. Dang, J., Xiao, J., Duan, Z.: Effect of pore structure and morphological characteristics of recycled fine aggregates from clay bricks on mechanical properties of concrete. Constr. Build. Mater. **358**, 29455 (2022)
12. Jean, B., Liu, H., Zhu, X., Wang, X., Yan, X., Ma, T.: Enhancing the mechanical and durability properties of fully recycled aggregate concrete using carbonated recycled fine aggregates. Materials **17**(8), 1715 (2024)
13. Kursula, K., Perumal, P., Ohenoja, K., Illikainen, M.: Production of artificial aggregates by granulation and carbonation of recycled concrete fines. J. Mater. Cycles Waste Manage. **24**, 2141–2150 (2022)
14. Shen, Q., Pan, G., Bao, B.: A method for calculating the carbonation degree of CSH. Adv. Cem. Res. **30**(9), 1–32 (2018)
15. Bahrami, A., Hammad, M., Ullah, S.: Innovative materials and strategies for low-carbon concrete. Adv. Sustainable Concr. Constr. 51–77 (2025)
16. Tesovnik, A., Ottosen, L.M., Ducman, V.: Carbonation of lightweight alkali-activated aggregates based on biomass fly ash: effect on microstructure and leaching behavior. Case Stud. Constr. Mater. **23**, e05014 (2025)
17. Tang, Y., Qiu, J.: CO_2-sequestering ability of lightweight concrete based on reactive magnesia cement and high-dosage biochar aggregate. J. Clean. Prod. **451**, 141922 (2024)
18. Yaphary, Y.L., et al.: Utilization of CO_2 cured CSW-MSWIBA cold bonded aggregate into lightweight concrete products for masonry units. Constr. Build. Mater. **276**, 122203 (2021)
19. Shi, C., Wu, Y.: Studies on some factors affecting CO_2 curing of lightweight concrete products. Resour. Conserv. Recycl. **52**(8–9), 1087–1092 (2008)
20. Moro, C., Francioso, V., Lopez-Arias, M., Velay-Lizancos, M.: CO_2 curing of mortar with natural and recycled concrete aggregate: an environmental and economic assessment. Constr. Build. Mater. **399**, 132587 (2023)

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Chapter 18

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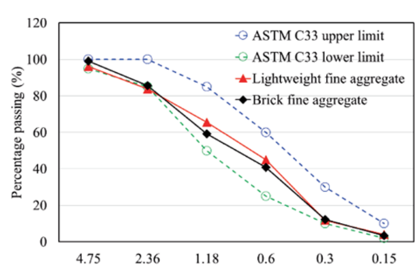
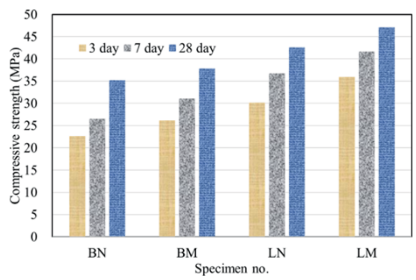
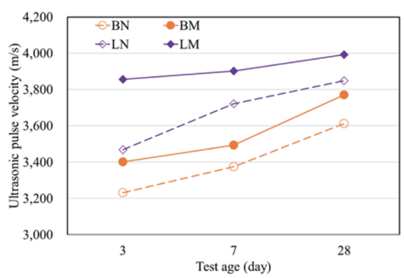
Alternative Texts for Your Images, Please Check and Correct them if Required

Page no	Fig/Photo	Thumbnail	Alt-text Description
4	Fig1		A metal bowl filled with a mound of bright red, granular powder. The background is a plain, light-colored surface.
4	Fig2		A metal bowl filled with a pile of small, mixed gray and reddish-brown gravel-like particles. The bowl has a number written on its side: "190933." The background is a plain, light-colored surface.
5	Fig3		A green gas cylinder secured with a chain, connected to a regulator and hoses. The cylinder is standing upright on a concrete floor, next to a wall with various cables and pipes. The setup appears to be part of a laboratory or industrial environment.
5	Fig4		A large laboratory environmental chamber with a front-facing door and a small window. The chamber has a control panel on the right side featuring several buttons, switches, and a digital display. The lower section has ventilation grilles. The chamber is situated in a well-lit room with a visible ceiling light.
5	Fig5		Line chart showing percentage passing versus sieve size in millimeters. The chart includes four lines: a blue dashed line for ASTM C33 upper limit, a green dashed line for ASTM C33 lower limit, a red line with triangles for lightweight fine aggregate, and a black line with diamonds for brick fine

<table>
<tr><th>Page no</th><th>Fig/Photo</th><th>Thumbnail</th><th>Alt-text Description</th></tr>
<tr><td></td><td></td><td></td><td>aggregate. The x-axis represents sieve size ranging from 4.75 mm to 0.15 mm, and the y-axis represents percentage passing from 0% to 120%. The lightweight and brick fine aggregate lines fall between the ASTM limits.</td></tr>
<tr><td>7</td><td>Fig6</td><td>
</td><td>Bar chart showing compressive strength in MPa for four specimens (BN, BM, LN, LM) over three time periods: 3 days, 7 days, and 28 days. Each specimen has three bars representing the different time periods, with compressive strength generally increasing over time. The 28-day bars are the tallest for each specimen.</td></tr>
<tr><td>8</td><td>Fig7</td><td>
</td><td>Line chart showing ultrasonic pulse velocity (m/s) over test age (days) for four different conditions: BN, BM, LN, and LM. The x-axis represents test age at 3, 7, and 28 days, while the y-axis shows velocity ranging from 3,000 to 4,200 m/s. BN and BM are represented by orange lines with circles, and LN and LM by purple lines with diamonds. All conditions show an increase in velocity over time, with LM having the highest values throughout.</td></tr>
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