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Optimizing the accelerated hardening of sawdust light weight concrete with carbon dioxide gas

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Abstract. Recent increases in the amount of industrial wastes to be removed has made dealing with such waste products and gases an issue that needs to be solved with some urgency. The accelerated hardening mechanisms of light weight concrete (LWC) using carbon dioxide gas were thus studied in an experimental study to investigate the mechanical performance of concrete incorporating waste sawdust. The final results were optimised to maximise strength and minimise density using two different parameters: gas concentrations and sawdust percentages. All samples were subjected to tests of their mechanical and physical properties, including compressive strength, splitting tensile strength, water absorption, and density using the relevant standards. Parts of the samples were also submitted to thermogravimetric analysis (TGA) following the process of accelerated curing in order to quantify the consumed calcium hydroxide ($\text{Ca}(\text{OH})_2$) and the produced calcium carbonate (CaCO_3). The results of the study showed an improvement in the physical and mechanical properties of all investigated specimens using the accelerated CO_2 curing method. In addition, a 7% sawdust addition with 53% CO_2 concentration resulted in higher strength in all cases. The TGA results proved that the carbonation curing resulted in lower $\text{Ca}(\text{OH})_2$ and higher CaCO_3 content, with associated enhancement in the mechanical performance. This indicates that CO_2 -rich industrial emissions could find a value adding use in carbonation curing of sustainable wood-based concrete.

Keywords: Accelerated curing, light weight concrete, carbonation, mechanical performance, sawdust, CO_2 and optimisation

1. Introduction

Light weight concrete fabrication from different material systems has been used extensively in the construction industry for many civil applications. Interest has increased substantially in Europe, America, and Asia since the 1940s in the development of concretes based on a mixture of wood and cement [1]. Wood-cement products are not new; however, it is only in recent years that these products have gained popularity based on developments in concrete curing techniques [2]. Successful development of wood-cement products could open a new method for the utilisation of waste wood in the future, though it was in the early twentieth century that pioneered studies regarding the beneficial effects of wood inclusion on the strength and deformation characteristics of concrete [3].

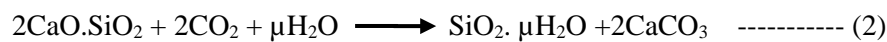
Light weight aggregate concrete is an important and versatile product due to its good mechanical properties, low density, sound insulation ability, durability, and good stability under the influence of weathering conditions [4]. It is often used in situations where either fire or moisture risks preclude the use of traditional wood products. Almost every study on wood-cement composites has focused on two distinct topics: assessing compatibility and manufacturing wood-cement products [5].

Compressive strength was used in assessing wood-cement compatibility when the composite was used as lightweight concrete masonry [6]. Findings showed that there were met the standard specifications for a lightweight non-loadbearing concrete block to be used in applications such as interior partitions". In spite of the attractive performance and wide application of wood-cement composites, slow setting times and expansion or swelling of the products have been pronounced problems. The most significant problem associated with manufacturing wood-cement composites is the long setting and pressing times of the composites that occur due to the slow hydration of the cement and the "poisoning" effect of wood particles on cement hydration [7]. One potential way to solve these problems is by the



accelerated hardening of wood-cement composites using carbon dioxide curing [8]. With the help of carbon dioxide, the time-consuming strength-gaining process of wood cement composites can be hastened.

Since the beginning of the industrial age, the concentration of CO₂ in the atmosphere has increased from 280 to 393 ppm [8]. The potential impacts of this increased CO₂ concentration in the air include acidification of ocean surfaces, acid rain, and exacerbated greenhouse effects [9]. As cement hydration products, such as calcium silicates and calcium hydroxide, can react with dissolved CO₂ in the presence of moisture, carbonation curing is an effective way to sequester CO₂ from the air. Various concrete products can benefit from CO₂ curing, including non-reinforced concrete masonry units, porous concrete, and wood-based concrete. The carbonation products are calcium carbonate and silica gel, and the reactions are described by Equations 1 and 2 [10].



The ultimate fate of a hardened cement paste is to be converted into calcium carbonate and hydrated silica by the reactions of calcium hydroxide and calcium silicate hydrate with atmospheric carbon dioxide [11, 12]. Carbonation of concrete has been extensively studied because of sustainability requirements and concerns about its durability. The carbonation of cement generally leads to increases in strength and dimensional stability, but it does cause irreversible carbonation shrinkage and reduces the pH value of the pore solution of the concrete.

2. Objectives

The overall objective of this paper is to develop, and assess the performance of, an accelerated carbonation curing treatment for light weight concrete in which CO₂ gas flows through the porous concrete media, diffusing through the pores, during carbonation curing. Another objective is to reduce the issue of industrial wastes (CO₂ and sawdust) through developing sustainable processing that opens up a new field of applications.

3. Materials and Mix Proportions

The experimental programme investigated light weight concrete made by mixing waste sawdust particles of up to 4.75 mm with ordinary Portland cement, fine and coarse aggregates, and tap water. Pre-treatment of the sawdust was done to inhibit the poisoning effect of the extractable substances such as soluble carbohydrates, waxes, and resins, on the setting and hardening of the concrete. This was done by boiling the sawdust in water containing 20% hydrated lime for one hour [13]. Table 1 show the grading of sawdust particles and fine aggregates used in this paper. Three different replacement percentages of sawdust by weight of fine aggregate were used for the investigation. The sawdust was obtained from a local sawmill. The physical properties of the utilised sawdust are documented in Table 2. All results indicated that the cement is conformed to Iraqi Specification No. 5/1984. The coarse aggregate was of 19 mm maximum size and the properties of the coarse and fine aggregates conformed to Iraqi Specification No. 45/1984 (sand/ zone 2).

Table 1: Grading of sawdust particles and fine aggregate.

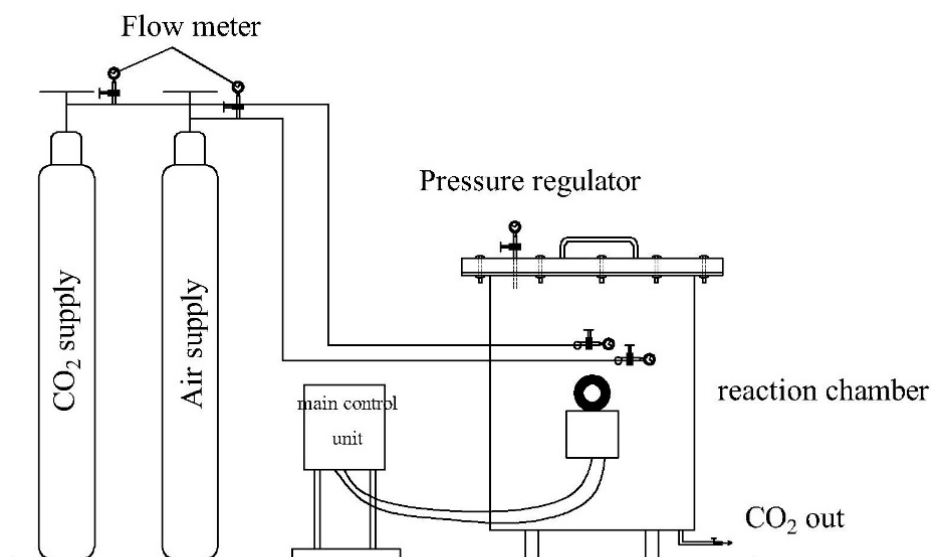
Item	Sieve size (mm)						
	10	4.75	2.36	1.18	0.60	0.30	0.15
Fine aggregate	100	94.3	78.2	55.7	43.3	14.9	6.1
Sawdust	100	80.5	37.4	12.8	6.7	4.5	1.7

Table 2: Physical properties of sawdust particles.

Property	Test according to ASTM D 4442 – 03 and ASTM D 2395 – 07a
Dry density (kg/m ³)	627.4
Moisture content (%)	61.4
Specific gravity	0.65
Water absorption (%)	179

4. Experimental Set-up

A total of 80 specimens, 48 cubes of 100 x 100 x 100 mm and 32 cylinders of 100 x 200 mm, were prepared according to BS 1881: Part 108: 1983 and BS 1881: Part 110: 1983 standards, respectively. Based on previous studies, the experimental variables included the CO₂ concentration at 0, 25, 50, and 75%, and the percentage of sawdust particles at 0, 10, 20, and 30% by weight of fine aggregate. The concrete used in this experimental program was made using mixes designed in accordance with ACI committee 211.2-04 to produce a structural light weight aggregate concrete (SLWAC) with a designed compressive strength of 18 MPa. The water to cement ratio was selected to be high enough to provide moisture for carbonation reactions and low enough to leave enough pore space for CO₂ penetration. Details of the mix design are shown in Table 3. All the concrete specimens were demoulded 24 hours after casting, then placed in moist curing for three days, followed by CO₂ curing for two hours. The specimens were dried at 105 ± 2 °C for thirty minutes before CO₂ curing to provide surface pathways for CO₂ gas to enter [5]. After 28 days, compressive strength, density and water absorption tests were made on the 100 mm cubes according to BS 1881: Part 116: 1983, BS 1881: Part 114: 1983 and BS 1881: Part 122: 1983 standards. Meanwhile, splitting tensile strength tests were done on the 100 mm diameter x 200 mm long cylinders according to BS 1881: Part 117: 1983 standards. To check whether accelerated carbonation had occurred, thermogravimetric analysis (TGA) was undertaken with SHIMADZU equipment using an STA 60 simultaneous analysis system on 50-mg samples with a dynamic nitrogen stream (flow rate = 30 mL/min) at a heating rate of 20 °C/min.

**Figure 1:** CO₂-curing Experimental set-up.

The main objectives of the optimization process in this phase of the research were to maximize compressive strength and to minimize density. Two effective variables, identified during the objectives phase of the study (CO₂ concentration and sawdust percentage), were selected to be optimized. Optimization software (Sigma XL Version 6.11/2011) was used to conduct an analysis of the response surface method (RSM), using Design of Experiments (DOE) principles.

Table 3: Mix proportions for all concrete samples.

Sample	Mix proportions (kg/m ³)					w/c %
	Cement	Sawdust	Fine aggregate	Coarse aggregate	Water	
Control	287	0.00	516	720	135	47
SD*-10	287	51.60	464.4	720	135	47
SD-20	287	103.2	412.8	720	135	47
SD-30	287	154.8	361.2	720	135	47

SD-10= Mix containing sawdust of x% concentration by weight of fine aggregate.

5. Results and Discussion

The average results of 28-day compressive strength were measured and are presented in Table 4 and Figure 2. It was observed that the compressive strength of sawdust concrete decreased when the sawdust/sand ratio increased, and the compressive strength increased when the CO₂ concentration increased, based on the same water to cement ratio. It was also seen that concrete made with 10% sawdust (SD-10) had a higher compressive strength compared to all other mixes (control, SD-20 and SD-30) by 57, 48, and 42%, respectively. These findings indicate that the compressive strength is directly related to both sawdust/sand ratio and carbonation curing.

The results of concrete density were observed to decrease from 1752.8 kg/m³ to 1685.5, 1596.7, and 1515.3 kg/m³ when the sawdust/sand ratio increased by 10, 20 and 30%, respectively, as shown in Table 4 and Figure 3. Further, the density compared to control mix increased as the CO₂ concentration increased. As expected, there was a direct relationship between compressive strength and density for all samples. A maximum increment in density was observed of 3.7% for mix SD-10 at 75% CO₂ concentration.

The results of water absorption for all samples are shown in Table 4 and Figure 4. Increasing the sawdust/sand ratio increased the water absorption of concrete such that the higher the sawdust content, the higher the water absorption. This is due to the lower sawdust density associated with the greater porosity of wood. The water absorption ability of concrete with sawdust was also affected by carbonation curing. Higher CO₂ concentrations resulted in significantly reduced water absorption values in most treatments.

Table 4: Experimental Results for all concrete samples at 28 days.

Sample	CO ₂ %	f _c MPa	f _t MPa	W.A %	D kg/m ³	Density increment %
Control	0	18.65	2.50	2.12	1752.8	0
	25	19.15	2.76	1.97	1761.2	0.5
	50	19.71	2.83	1.80	1778.6	1.5
	75	20.17	3.09	1.73	1786.9	1.9
SD-10	0	15.92	1.78	3.79	1685.5	0
	25	17.84	1.91	3.06	1703.7	1.1
	50	19.23	2.06	2.41	1726.1	2.4
	75	21.52	2.22	1.89	1748.6	3.7
SD-20	0	12.40	1.53	6.18	1596.7	0
	25	15.13	1.58	4.52	1618.4	1.4
	50	16.89	1.72	3.31	1639.1	2.7
	75	17.70	1.87	2.67	1654.8	3.6
SD-30	0	9.31	1.39	8.71	1515.3	0
	25	11.25	1.54	6.57	1539.1	1.6
	50	12.58	1.67	4.72	1561.7	3.1
	75	13.31	1.73	2.95	1578.4	4.1

f_c= compressive strength in MPa, f_t= splitting tensile strength in MPa,

D= density in kg/m³, W.A= water absorption (%).

The relationship between splitting tensile strength and sawdust content appeared to be more linear than those of compressive strength and density and sawdust content. Table 4 and Figure 5 summarise the splitting tensile strength to sawdust content and CO₂ concentration relationships. As with the compression test results, the splitting tensile strength decreased as the sawdust content increased in the mix, and all samples had higher splitting tensile strength after carbonation curing than the control mixes at the same sawdust/sand ratios.

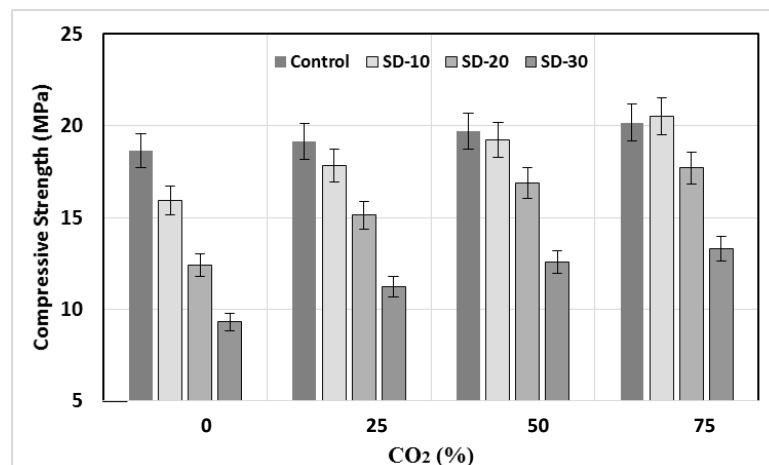


Figure 2: Relationship between compressive strength and CO₂ concentrations of different sawdust/sand ratios.

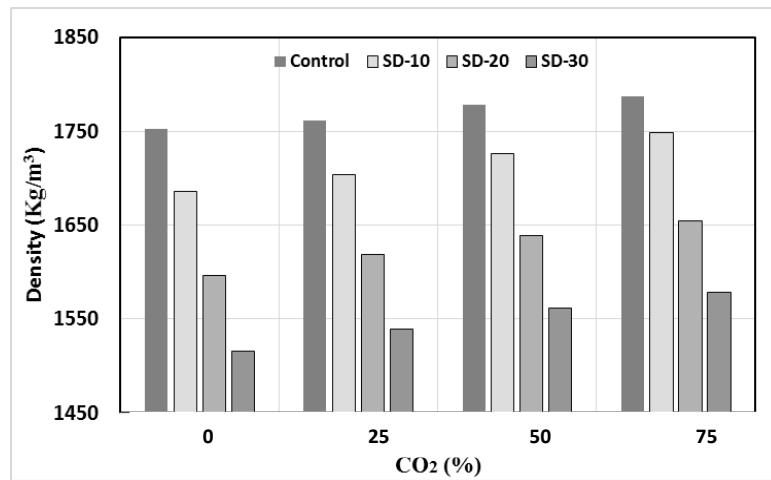


Figure 3: Relationship between density and CO₂ concentrations of different sawdust/sand ratios.

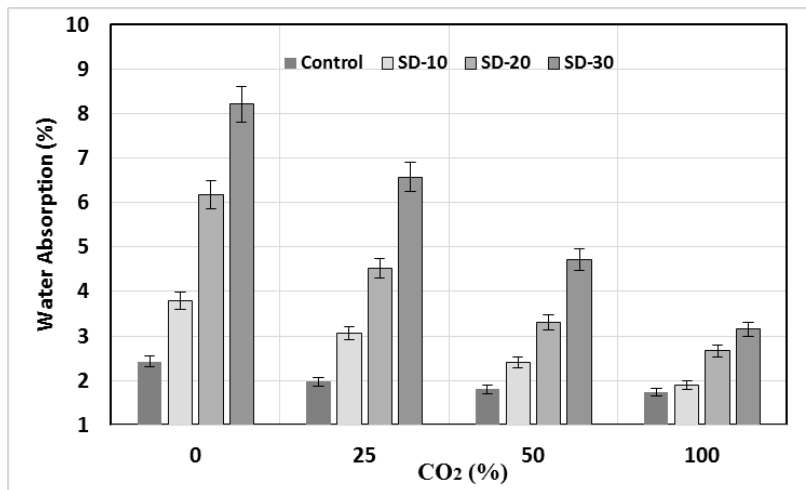


Figure 4: Relationship between water absorption and CO₂ concentrations of different sawdust/sand ratios.

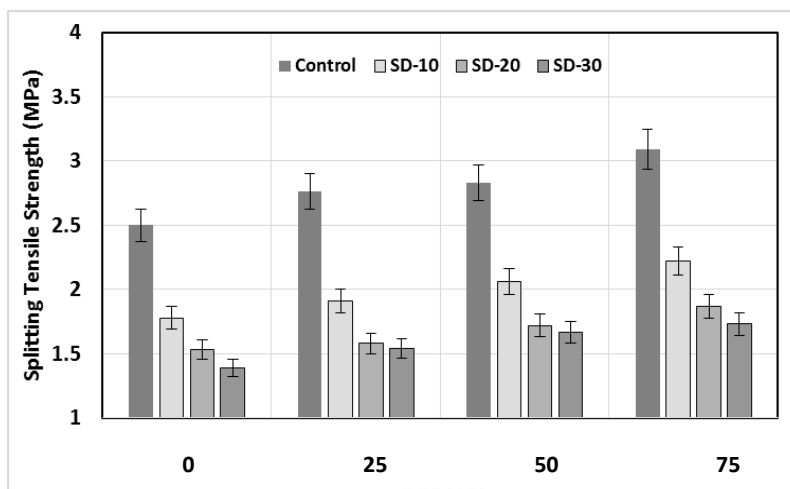


Figure 5: Relationship between splitting tensile strength and CO₂ concentrations of different sawdust/sand ratios.

The results in Table 5 show that after CO₂ curing, there was a decrease in the Ca(OH)₂ content that was associated with an increase in the CaCO₃ content. This was the main reason for the increases in the density, compressive strength and splitting tensile strength. It was also responsible for the reduction in water absorption after carbonation curing, which was due to petrification of sawdust particles when the CaCO₃ diffused into empty spaces. The formation of solid products, mainly CaCO₃, in the pores during carbonation decreased the porosity of concrete during accelerated CO₂ curing. The CaCO₃ content thus seemed to generally correlate with the strength and density of light weight concrete as far as the effects of CO₂ curing were concerned. Briefly, such carbonation can be described as the diffusion of CO₂ through the unsaturated pores in a cementitious matrix. CO₂ is dissolved in the aqueous phase in the pores, becoming carbonic acid (H₂CO₃), which dissociates to HCO₃⁻ and CO₃⁻ ions [14]. This product reacts with the product of the dissolution of Ca(OH)₂, releasing Ca²⁺ ions and OH⁻, as well as precipitating to form calcium carbonate (CaCO₃) through surrounding sawdust particles, leading to petrification of the wood that maximises its size and makes the ITZ thicker and stronger.

Table 5: TGA results for all concrete samples.

Sample	CO ₂ %	Ca(OH) ₂ %	CaCO ₃ %
Control	0	6.71	14.22
	25	6.38	15.31
	50	5.14	15.97
	75	4.22	16.30
SD-10	0	7.82	14.76
	25	6.48	16.03
	50	5.21	16.74
	75	4.66	17.26
SD-20	0	8.34	15.08
	25	7.19	16.21
	50	6.05	16.94
	75	5.39	17.57
SD-30	0	8.87	15.63
	25	7.24	16.92
	50	6.21	17.89
	75	5.47	19.41

In order to gain a complete understanding of the properties of Sawdust Light Weight Concrete (SDLWC) and its dependence on composition and curing media, the results of the mechanical properties were optimised using SigmaXL Version 6.1/11 to perform an analysis of the response surface method (RSM). According to the optimisation process (Figures 6 and 7), the optimum curing percentage of carbon dioxide gas is 53%, with an optimum sawdust to sand ratio of 7%. These percentages maximised the strength of the light weight concrete samples and reduced the density of the end product to produce a balanced gain between strength and density.

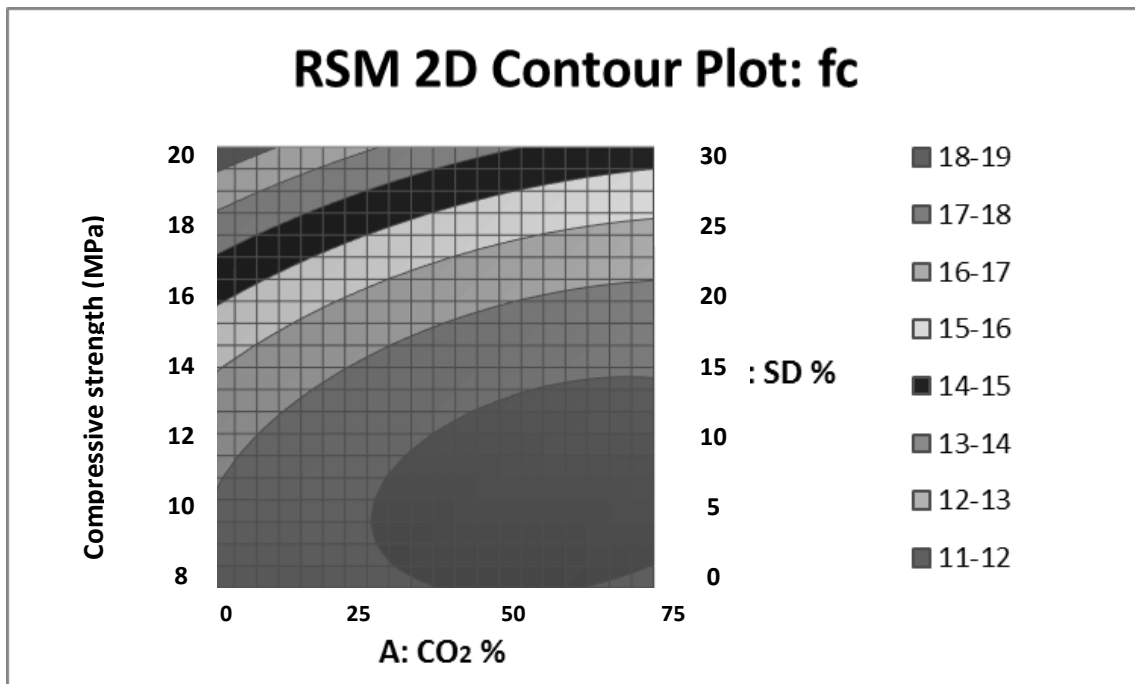


Figure 6: Maximum 2-D compressive response surfaces plots between CO₂ concentrations and sawdust ratios.

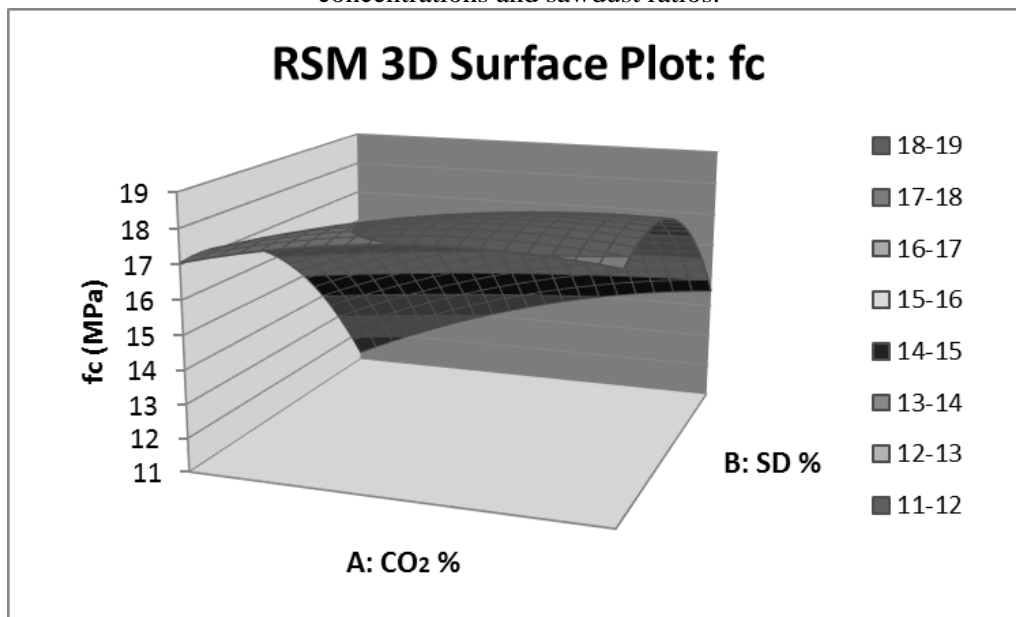


Figure 7: Maximum 3-D compressive response surfaces plots between CO₂ concentrations and sawdust ratios.

6. Conclusions

From this investigation, the following conclusions were derived:

1. The strength of sawdust light weight concrete was positively affected by carbonation reactions; approximately 35% of the ultimate compressive strength was obtained by carbon dioxide curing, which also reduces the water absorption due to pore refinement.

2. The addition of sawdust particles into concrete affects the mechanism of carbonation curing, producing better CO₂ uptake, compatibility, and strength of sawdust by providing empty spaces for carbonates to form.
3. The TGA results proved that the calcium hydroxide decreased with the increase in calcium carbonate after carbonation curing.
4. A higher compressive strength of 21.52 MPa was found for the mix containing 10% replacement of sawdust particles by weight of sand exposed to 75% CO₂ concentration. This made it clear that higher composite density gives higher compressive strength.
5. Most of the investigated mixes had an average cube strength of less than 21 MPa; thus, these should not be used as a structural light weight concrete following CO₂ curing techniques.
6. According to the optimisation results, the optimum sawdust/sand ratio was 7% associated with a 53% CO₂ concentration.

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