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Eco-friendly Super Sulphated Cement Concrete Using Vietnam Phosphogypsum and Sodium Carbonate Na_2CO_3

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Abstract

Sustainable development is one of the critical topics in the construction industry today, especially in reducing CO_2 emissions and production energy costs. There have been many studies worldwide on using ground granulated blast furnace slag combined with phosphogypsum (PG) to replace binder (B) in making concrete. However, this topic in Vietnam has not received much attention despite the large backlog of phosphogypsum waste. One of the main disadvantages limiting the feasibility of super-sulphated binders in concrete is the relatively slow hydration and hardening processes, which affect the rate of strength development of mortar and concrete, especially at an early age. In this study, the use of Na_2CO_3 salt as a quick, solid additive can overcome the disadvantages of this type of binder. Research results show that using 15 to 25% phosphorus gypsum waste (PG) and a combination of 60 to 80% finely granulated blast furnace slag (GGBFS) with a small amount of cement and an activator like Na_2CO_3 can replace cement in making concrete. The concrete mix has good workability, and the maximum compressive strength after 28 days can reach over 50 MPa. Using industrial wastes as the main ingredients to make binders will improve sustainable development, reducing environmental pollution and the cost of mortar and concrete products in construction.

Keywords: Concrete; Industrial Waste; Ground Granulated Blast Furnace Slag; Phosphogypsum; Super Sulphated Cement.

1. Introduction

Environmental pollution is a topic attracting the attention of all countries worldwide. The massive development of industrial production in general and the production of building materials, in particular, has posed the problem of increasing emissions and waste, requiring reuse to avoid environmental pollution. Therefore, the research and use of industrial wastes to manufacture building material products have both technical and economic significance, ensuring green and sustainable production. One of the most promising alternative cementing systems is super-sulphated cement (SSC). This binder is mainly composed of ground granulated blast furnace slag (GGBFS), gypsum, and a small amount of alkali activator (such as quick lime, clinker cement, or cement) [1, 2]. Compared with ordinary Portland cement, super-sulphated cement has many advantages, such as low hydration heat evolution, good sulphate resistance, less clinker, and more gypsum. Thus, more solid waste can be consumed [3–6]. This binder can consume a large amount of gypsum in general, phosphogypsum (PG) in particular, and blast furnace slag.

Phosphogypsum is a by-product in the fertilizer industry of the wet production of phosphoric acid (H_3PO_4). In Vietnam, the mountain of phosphogypsum waste is tens of meters high. Many hectares with a reserve of 3.5 million tons of DAP Vinachem Joint Stock Company are in Dinh Vu Industrial Park - Vietnam, causing many people to worry about

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environmental dangers, which have existed for many years, have not been resolved. A problem posed is how to effectively promote 2.56 million tons of PG residues in DAP while public opinion is concerned that PG residues pollute the environment because they contain many toxic substances such as HF acid, H_2SO_4, H_3PO_4 and heavy metal salts [1]. PG is used in several areas with high technical and economic feasibility.

Currently, there have been many studies on using sulphate concrete in construction, such as levelling material in the form of a cement-reinforcing mixture, as a foundation layer in the construction of roads and highways [4, 5]. Concrete made from mixed binder using PG has also been studied extensively globally [6-8]. Singh studied a high-strength binder based on anhydrous PG (high-temperature calcined gypsum), fly ash, GGBFS, and ordinary Portland cement [8]. The study results also show that this binder is suitable for partial replacement (maybe up to 25%) of cement in concrete without causing any adverse effect on strength. Blast furnace slag is the by-product of the iron and steel industry, forming particles with diameters from 10 mm to 200 mm. GGBFS is a common material used worldwide in cement production because it gives cement many remarkable properties such as durability in a seawater environment, resistance to sulphate, low heat, suitability for large concrete blocks, and good waterproofing [9-11].

With the main components of gypsum and GGBFS, SSC-based materials also have drawbacks of their own with mechanical properties, such as lower initial strength, higher drying shrinkage and lower resistance to carbonation when compared to ordinary Portland cement [12, 13]. In general, high strength at an early-age of SSC can be achieved by increasing the basicity in the binder solution sodium. Several studies have shown that the low initial strength of binders containing high content of GGBFS can be overcome by adding alkaline activators (e.g., OPC [14, 15], KOH [16], sodium hydroxide [17], sodium silicate or sodium sulphate [18]). Circulating fluidized bed combustion fly ash can be used as the alkaline activator which contains anhydrite and portlandite [19]. However, SSCs activated by materials with strong basicity are difficult for industrialization due to low controllability, strong corrosion, high cost, and strict processing requirements [20, 21]. Na_2CO_3 is more feasible and cheaper and shows less corrosivity and harm to the environment [22-24].

Since GGBFS is the main ingredient accounting for the most significant amount in SSC, the use of Na_2CO_3 to activate GGBFS also contributes to promoting the hydration of SSC. The approach and significance of this paper are using Na_2CO_3 in making SSC and concrete based on SSC. Previous studies have investigated using sodium carbonate (Na_2CO_3) source to activate GGBFS [25-27]. Abdalqader et al. [28] reported an effect on the compressive strength of using Na_2CO_3 to activate a mixture of fly ash and slag. The authors note that the strength of the Na_2CO_3 activated fly ash-slag mixture increased with the curing time and the Na_2CO_3 content and that the strength at the early ages depended on this Na_2CO_3 content.

According to Wang et al., the mixture of CaO and Na_2CO_3 can improve the density of hardened pastes and significantly speed up the formation of hydration products [25]. Na_2CO_3 was also used by Kim et al. to enhance the mechanical characteristics of high-volume slag cement (50 percent OPC and 50 percent GGBF) [29]. The findings demonstrated that there was a trend of increasing high-volume slag cement sample strength with the increase of Na_2CO_3 content. Among the Na_2CO_3-activated high-volume slag cement samples, the 5% Na_2CO_3-activated high-volume slag cement paste showed the greatest combination of early to later-age strength growth as well as the highest ultrasonic pulse velocity and the lowest amount of water absorption. Currently, the research on the use of Na_2CO_3 as an activator in SSC is still very rare. In this study, Na_2CO_3 is used to improve the hardening of the super sulphated cement at an early age and at the same time as a basis for making concrete using phosphogypsum waste, contributing to producing low-cost, good-quality concrete that meets the needs of construction.

2. Materials and Research Methods

2.1. Materials

Materials used in the study include Phosphogypsum (PG); commercial ground granulated blast furnace slag S95 (GGBFS); But Son Cement PC40 (C); crushed stone originating from carbonate rock; fine aggregates; activator Sodium Carbonate (Na_2CO_3); Silica fume of Elkem (SF) and Polycarboxylate superplasticizer (SP). The technical properties and chemical composition of the materials used are presented in Tables 1 to 6.

Table 1. Chemical composition of materials used in the study

Oxide	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	MnO	L.O.I
C	20.3	5.05	3.51	62.81	3.02	-	-	2	-	-	1.83
PG	2.99	0.87	0.56	28.07	0.69	0.03	0.56	42.5	2.93	0.39	19.92
GGBFS	34.52	0.66	12.38	41.54	7.25	0.43	0.24	1.37	-	-	0.96

Table 2. Properties of ground blast furnace slag used in the study

Characteristic	Unit	Result
Density	g/cm^3	2.96
Strength activity index	%	106.2
Mean particle size	µm	10.8
L.O.I	%	0.96

Table 3. Physical and mechanical properties of But Son Cement PC40

Characteristic	Unit	Result
Blaine fineness cm^2/g	%	3910
Consistency	%	29.5
Initial setting time	Min	120
Final setting time	Min	215
Compressive at 3 days	MPa	28.8
Compressive at 28 days	MPa	53.1
Density	g/cm^3	3.12

Table 4. Characteristic of coarse aggregate

Characteristic	Unit	Coarse aggregate size	
		5-10 mm	10-20 mm
Specific density	g/cm^3	2.70	2.70
Bulk density	%	1620	1570
Porosity	%	41.0	43.6
Content of dust, mud and clay	%	0.12	0.11

Table 5. Characteristic of river sand

Characteristic	Unit	Result
Density	g/cm^3	2.66
Bulk density	kg/m^3	1465
Porosity	%	44.9
Finess Modulus	-	2.67
Content of dust, mud and clay	%	0.2

Table 6. Characteristic of Silica fume

Characteristic	Unit	Result
Density	g/cm^3	2.21
L.O.I	%	4.20
SiO_2	%	93.45
Fe_2O_3	%	0.52
Al_2O_3	%	0.92
CaO	%	1.57
Strength activity index	%	116.5%

The grading curve of silicafume, ground granulated blast furnace slag, phosphogypsum and cement is presented in Figure 1.

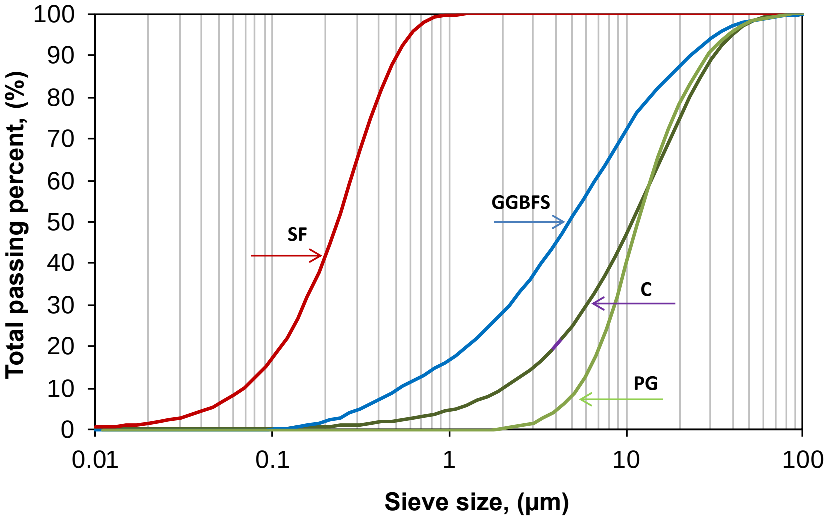

Figure 1. Grading curve for the used materials in SSC

2.2. Experimental Methods

The main technical properties of the materials used were determined according to Vietnamese standards presented in Tables 1 to 6. The mixing and moulding process of the binder sample is according to the procedure presented in the Figure 2.

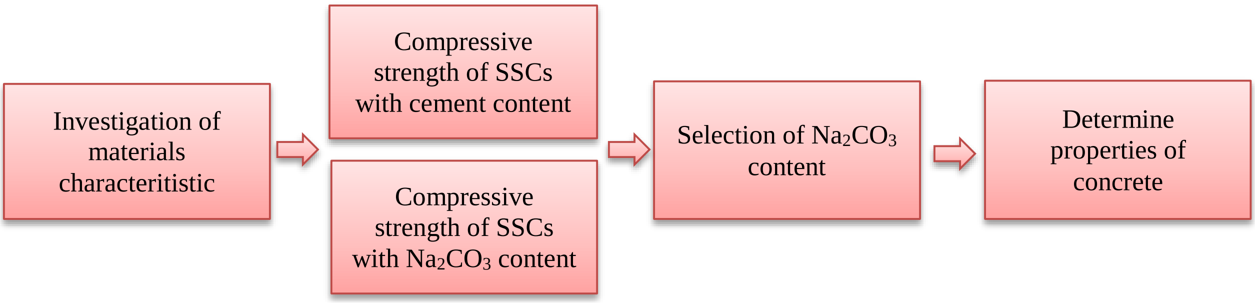

Figure 2. The research diagram

After mixing with water, the binder samples were cast in the moulds of 50×50×50 mm and cured in moulds for 24 ± 2 hours at laboratory temperature (20°C to 30°C). The compressive strength of the binder was measured at 3 and 28 days. The results reported are the average of three samples. Regarding the setting time of the binder, the ratio W/B was fixed at 0.325 and the Na_2CO_3 content at the optimal level to determine the cement's initial and final setting time.

The process of mixing concrete is mixed according to the following process: After mixing, the concrete mixture will be determined workability (slump), then cast in the mould 100×100×100 mm and cured at a temperature of 20 - 30°C. After 24 h, the samples were removed from the mould and continued soaking in water to the age for strength determination. The compressive strength of concrete was determined at 3, 28 and 90 days. The results reported are the average of three samples.

Figure 3. Workability test and concrete sample after compressive strength test

2.3. Proportion of Binders and Concrete

The influence of the content of PG, GGBFS, cement and Na_2CO_3 on the compressive strength of the binder was studied through 27 compositions with different binder ratios. The Na_2CO_3 is added in 2, 3 and 4% by weight. The W/B ratio is fixed at 0.325. The compressive strength of these binder samples was then compared with the control grade (100% cement) to see the efficiency of using gypsum waste and ground granulated blast furnace slag in the binder. The proportions of the ingredients for SSCs are shown in Table 7.

Table 7. Composition of binder mixture activated with Na_2CO_3

N°	Name of composition	wt. (%)				W/B
		GGBFS	PG	C	Na_2CO_3	
1	CP.85.10.5.2	85	10	5	2	0.325
2	CP.85.10.5.3	85	10	5	3	0.325
3	CP.85.10.5.4	85	10	5	4	0.325
4	CP.80.15.5.2	80	15	5	2	0.325
5	CP.80.15.5.3	80	15	5	3	0.325

6	CP.80.15.5.4	80	15	5	4	0.325
7	CP.75.20.5.2	75	20	5	2	0.325
8	CP.75.20.5.3	75	20	5	3	0.325
9	CP.75.20.5.4	75	20	5	4	0.325
10	CP.80.10.10.2	80	10	10	2	0.325
11	CP.80.10.10.3	80	10	10	3	0.325
12	CP.80.10.10.4	80	10	10	4	0.325
13	CP.75.15.10.2	75	15	10	2	0.325
14	CP.75.15.10.3	75	15	10	3	0.325
15	CP.75.15.10.4	75	15	10	4	0.325
16	CP.70.20.10.2	70	20	10	2	0.325
17	CP.70.20.10.3	70	20	10	3	0.325
18	CP.70.20.10.4	70	20	10	4	0.325
19	CP.75.10.15.2	75	10	15	2	0.325
20	CP.75.10.15.3	75	10	15	3	0.325
21	CP.75.10.15.4	75	10	15	4	0.325
22	CP.70.15.15.2	70	15	15	2	0.325
23	CP.70.15.15.3	70	15	15	3	0.325
24	CP.70.15.15.4	70	15	15	4	0.325
25	CP.65.20.15.2	65	20	15	2	0.325
26	CP.65.20.15.3	65	20	15	3	0.325
27	CP.65.20.15.4	65	20	15	4	0.325
28	CP.100	0	0	100	0	0.325

In this study, the aggregate mixture containing 40% particle size 5-10 mm and 60% grain size 10-20 mm is fixed. It was changing the amount of binder and W/B ratio to study the effect of SSC on slump and concrete strength. The composition of concrete in the test is presented in Table 8.

Table 8. Concrete mix composition using super sulphated cement

N°	Name of mixture	Amount of material used for 1m^3 of concrete mixture ((kg/m^3)										
		W/B	C	PG	GGBFS	SF	Na_2CO_3	Sand	Stone 10×20mm	Stone 5×10mm	SP (ml)	Water
CP1	80GGBFS_15PG_5C_0.35	0.35	22.5	67.6	360.9	23.8	14.25	780	528	352	7125	196
CP2	70GGBFS_20PG_10C_0.35	0.35	45.0	90.0	314.9	23.6	14.25	780	528	352	7125	195
CP3	60GGBFS_25PG_15C_0.35	0.35	67.3	112.1	269.1	23.6	14.13	780	528	352	7125	195
CP4	80GGBFS_15PG_5C_0.40	0.40	21.3	63.6	339.1	22.3	13.38	780	528	352	6750	207
CP5	70GGBFS_20PG_10C_0.40	0.40	42.3	84.5	295.9	22.3	13.38	780	528	352	6625	206
CP6	60GGBFS_25PG_15C_0.40	0.40	63.3	105.4	253.0	22.3	13.38	780	528	352	6625	206
CP7	80GGBFS_15PG_5C_0.45	0.45	20.0	60.0	319.9	21.0	12.63	780	528	352	6250	217
CP8	70GGBFS_20PG_10C_0.45	0.45	39.9	79.8	279.1	21.0	12.63	780	528	352	6250	216
CP9	60GGBFS_25PG_15C_0.45	0.45	59.6	99.5	238.6	20.9	12.50	780	528	352	6250	216

3. Results and Discussion

The study aims to make an SSC with compressive strength equivalent to grade 40 cement and, simultaneously, overcome the disadvantages of this binder. It means that the process of hydration and solidification will occur faster. The properties of the studied binder include compressive strength and setting time. The compressive strength of the binder samples was compared with the control grade to observe the efficiency of using waste phosphogypsum waste and blast furnace slag in the binder. The workability and compressive strength of concrete using super sulphated cement were also determined to choice the optimum binder proportion used for concrete.

3.1. Effect of Cement Content on The Compressive Strength of Super Sulphated Cement

The effect of cement content on the compressive strength of binder samples at the age of 3 days and 28 days are shown in Figures 4 to 9.

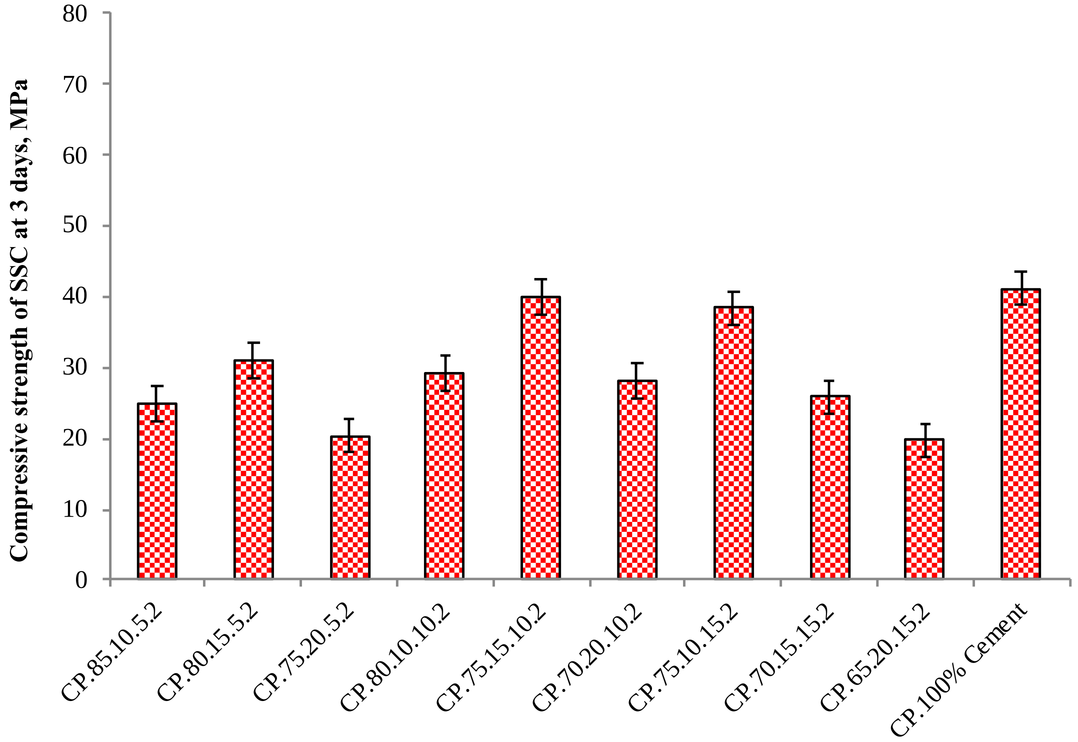

Figure 4. Compressive strength of SCC samples using different cement content and 2% Na_2CO_3 at 3 days

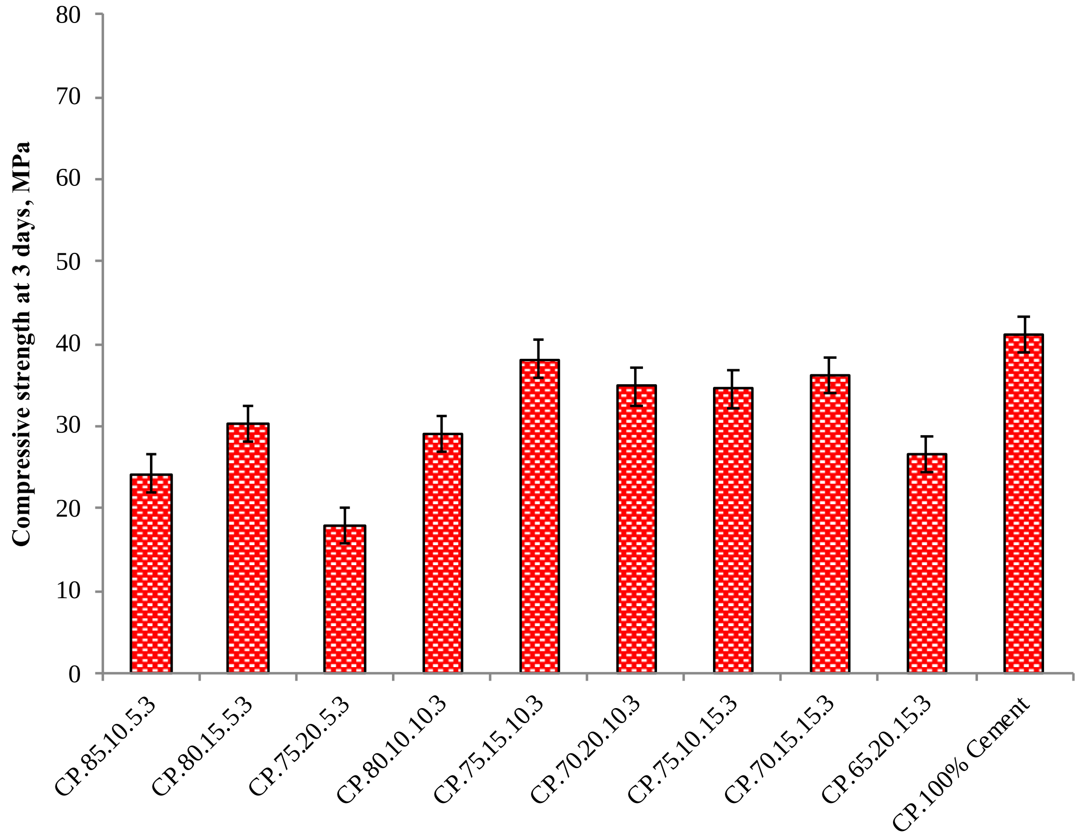

Figure 5. Compressive strength of SCC samples using different cement content and 3% Na2CO3 at 3 days

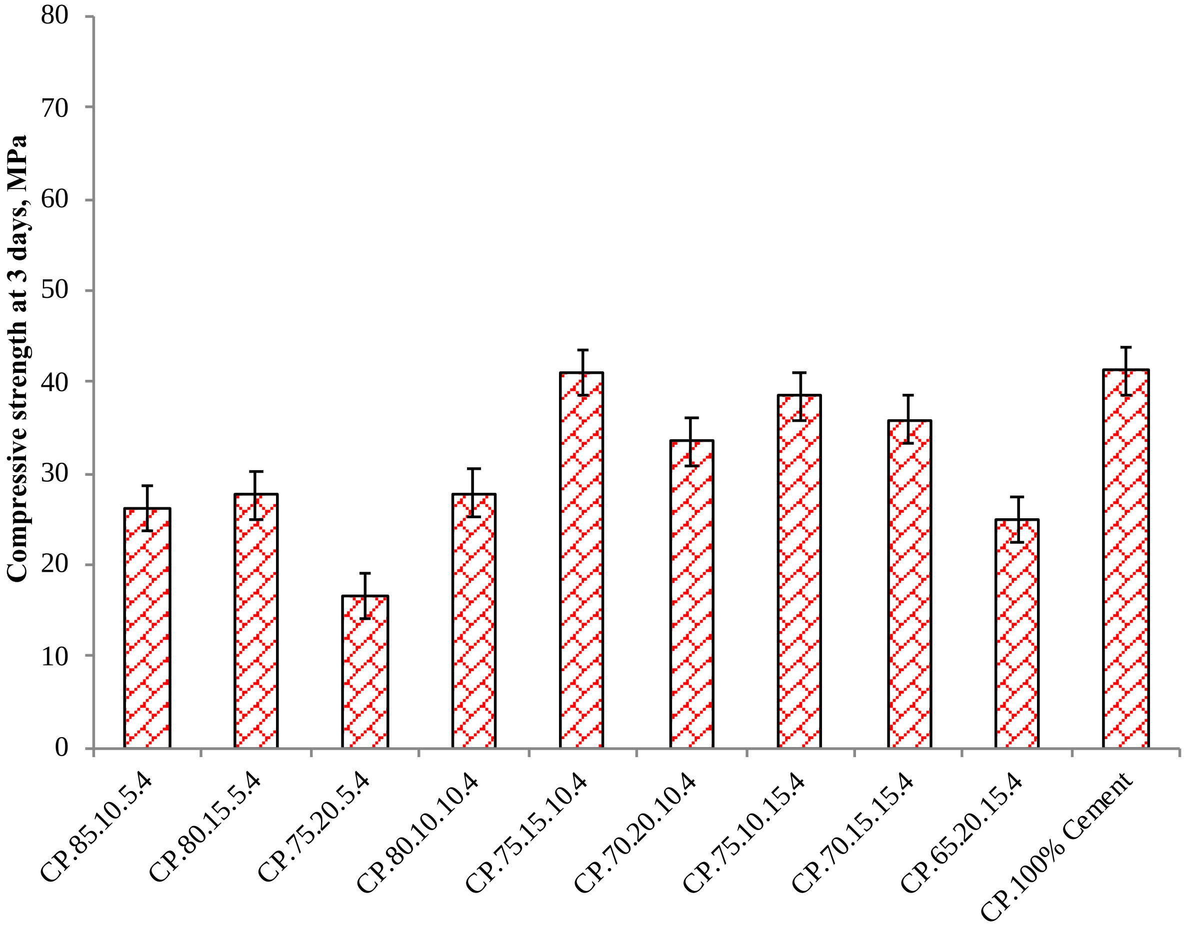

Figure 6. Compressive strength of SCC samples using different cement content and 4% Na_2CO_3 at 3 days

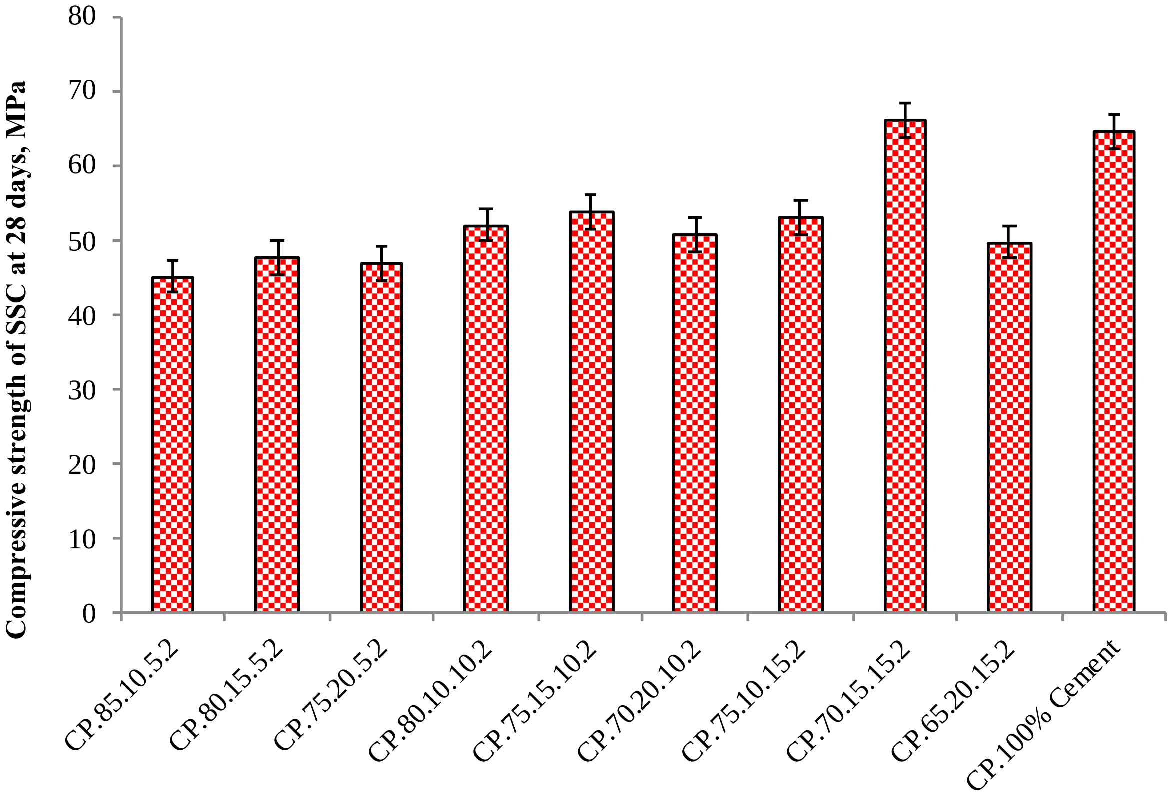

Figure 7. Compressive strength of SCC samples using different cement content and 2% Na_2CO_3 at 28 days

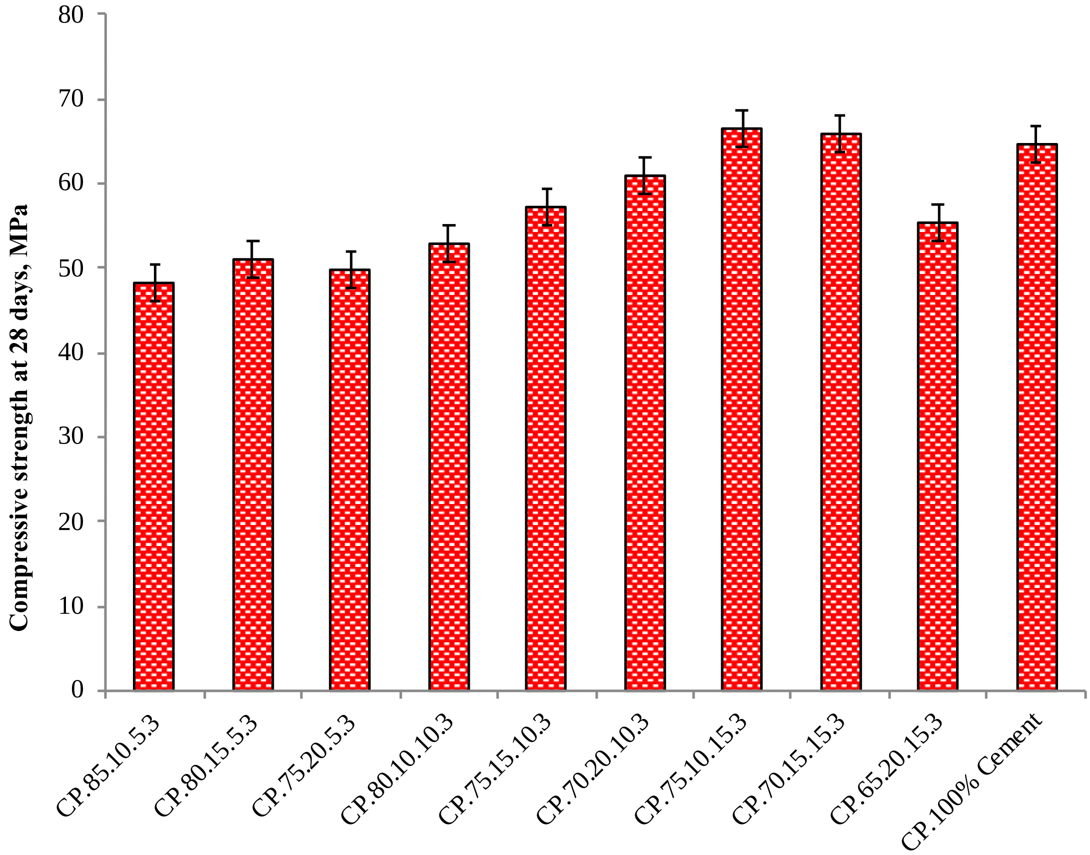

Figure 8. Compressive strength of SSC samples using different cement content and 3% Na_2CO_3 at 28 days

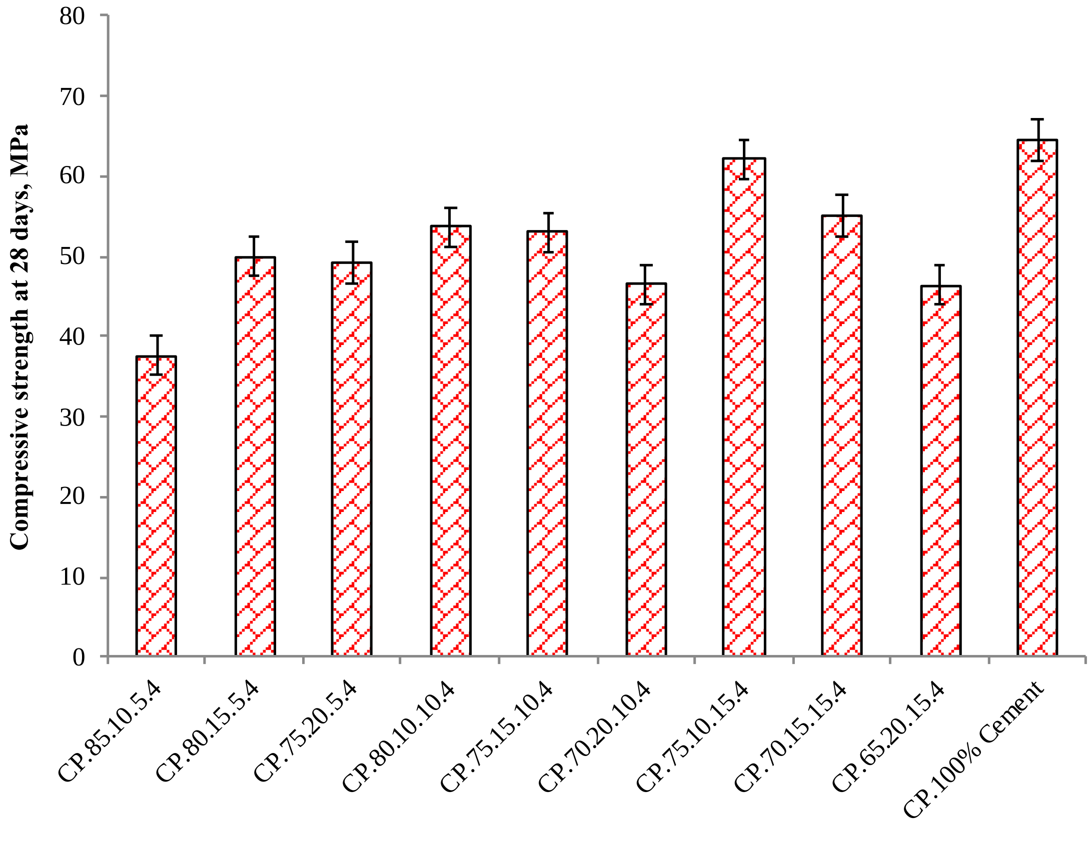

Figure 9. Compressive strength of SSC samples using different cement content and 4% Na_2CO_3 at 28 days

The above results show that: The strength at the age of 3 days of the binder samples depends mainly on the cement content used, the strength of the binder samples mostly does not reach 40 MPa, and the difference in strength value between the samples is significant. The strength of the binder group using 5% cement was lower than that of the group using 10% and 15%, in which sample CP.70.20.5 had the lowest compressive strength value. When increasing the cement content to 10%, the compressive strength at the age of 3 days of sample CP.75.15.10 reached the highest value (Figures 4 to 6).

At the age of 28 days, it can be seen that most of the binder samples have compressive strength above 40 MPa. This strength development process is related to C-S-H formation thanks to the ability of cement and gypsum to activate GGBFS. According to Bernal et al. [27], the early-age reaction in a CO_3^{2-} activated binder happens when Ca^{2+} produced by slag dissolution interacts with CO_3^{2-} in the pore solution. They stated that having enough Ca^{2+} might lead to consume CO_3^{2-} at early-age, which would increase the hydration of slag after the exhaustion of CO_3^{2-}. In order to consume carbonate, OPC was employed in this study as a calcium source. As a consequence, it is clear that the addition of Na_2CO_3 increased the strength of the SSCs by causing the development of more C-S-H and calcite. This result is in agreement with previous studies [28-31].

However, the compressive strength of SSCs is reduced when the proportion of cement in the binder increases to 15%, especially in the composition containing high content of PG. The reason may be that Ca^{2+} ions accumulate and increase alkalinity in the hydrating process at a late age. More bundled ettringite is formed, causing crystal pressure to crack the structure and causing strength loss [31-34]. Therefore, the cement content in the binder should not exceed 15%. The law of influence of cement content on binder strength is similar to that of early age, but the extent is less pronounced. The compressive strength of sample CP.75.10.15.3 reached the highest value of 66.4 MPa - higher than that of the control cement mortar sample with a strength of 64.5 MPa (Figure 8). The compressive strength of sample CP.85.10.5.4 reached the minimum value of 37.6 MPa (Figure 9). Binder composition using 15% cement and 65% gypsum (grade group CP.65.20.15) still has the lowest strength.

3.2. Effect of the Content of Na_2CO_3 on the Compressive Strength of the Binder

One of the most significant disadvantages of the binder is that the strength at an early age is relatively low; even after 24 hours, the sample is still not hardened (still soft). Therefore, to increase the practicality of applying this binder, it is necessary to study the appropriate type and content of activating additives. The addition of Na_2CO_3 contributes to increasing the pozzolanic activity of GGBFS. It forms an additional amount of calcium silicate hydrate mineral C-S-H, promoting the binder's solidification and strength development [35]. The results of the influence of the Na_2CO_3 amount on the compressive strength of the binder are shown in Figures 10 and 11.

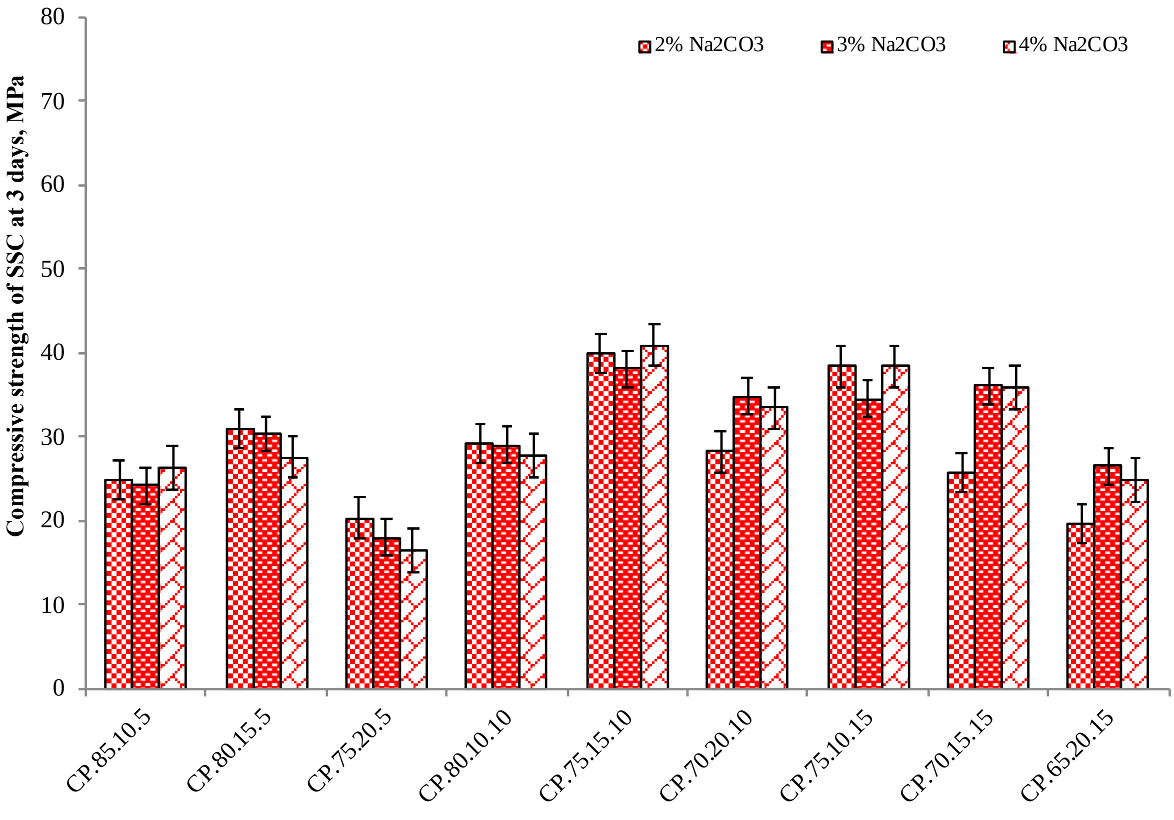

Figure 10. Compressive strength of binder samples using 2%, 3%, 4% Na_2CO_3 at 3-day age

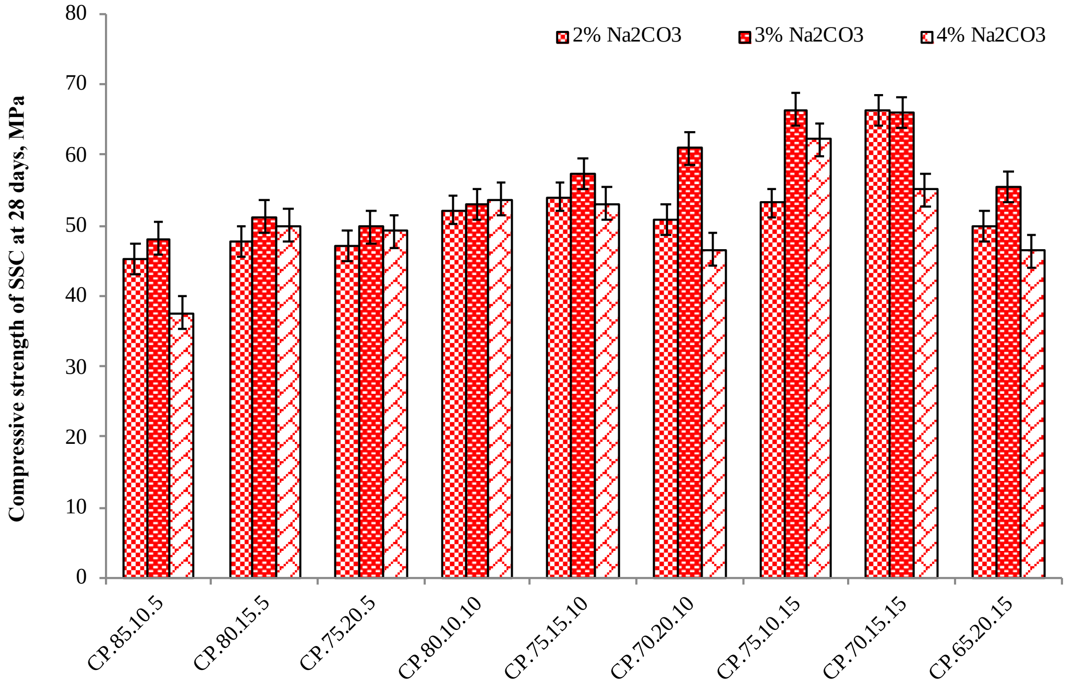

Figure 11. Compressive strength of binder samples using 2%, 3%, 4% Na_2CO_3 at 28-day age

The above results show that: The ability to activate strength at an early age (3 days) of the Na_2CO_3 is not evident for the binder group using 5% cement. After mixing with water, the hydration product is ettringite ($C_3A.3CaSO_4.32H_2O$), and C-S-H is formed. Ettringite formation drives the strength of this type of binder at an early age [20, 21, 36]. With the binder group using 5% cement, the amount of ettringite generated is insufficient to promote early strength. The compressive strength at three days of sample CP.75.20.5.4 reached the lowest value of 16.5 MPa (Figure 9).

When increasing the content of Na_2CO_3 from 2% to 4%, the strength of the binder does not change significantly. The optimal content of Na_2CO_3 is about 3% for the highest strength binder, and the composition containing 4% Na_2CO_3 almost has the lowest compressive strength. The compressive strength at 28 days of sample CP.75.10.15.3 reached the highest value of 66.4 MPa (Figure 11).

3.3. Setting Time of Super Sulphated Cement

The study fixed the ratio of Water/Binder at 0.325 and the Na_2CO_3 content at 3% to determine the initial and final setting time. The experimental results are shown in Figure 12.

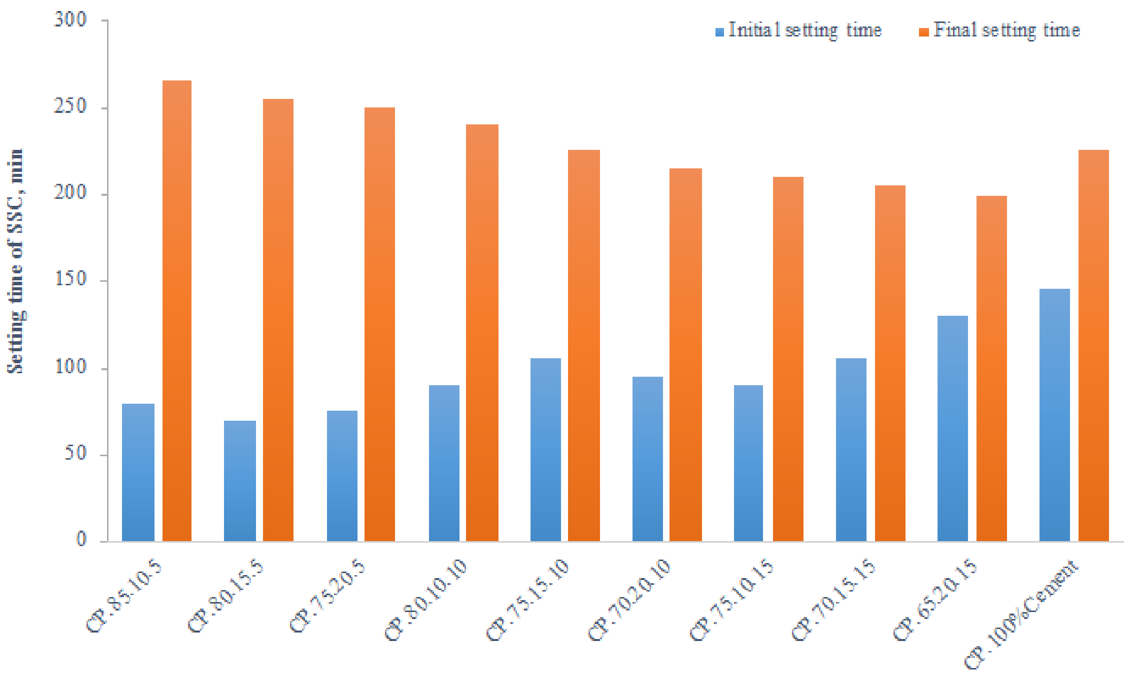

Figure 12. The setting time of binder samples compared with control samples

From the results in Figure 12, some critical observations are easily discerned about the setting time of the binder samples. When the cement content increases from 5 % to 15 %, the initial setting time seems to be lengthened, but the final setting time tends to be shorter. The binder sample using 5% cement had the shortest setting time, ranging from 70 minutes to 80 minutes, but the longest setting time, from 250 minutes to 260 minutes. Meanwhile, the control sample (CP.100 - 100% cement, ratio W/C= 0.325) had an initial setting time of 145 minutes and a final setting time of 225 minutes.

The study's results showed no difference among the compositions using 5% or 10% cement. Meanwhile, the group of samples using 15% cement clearly showed the trend of lengthening the initial setting time and shortening the final setting time when the gypsum content increased from 10% to 20% (corresponding blast furnace slag content is reduced). This result may be due to the early formation of ettringite, which inhibits the initial hydration of the cement. After mixing with water, the gypsum begins to dissolve, and the sulphate ion will quickly saturate in the solution. At the same time, the cement will also begin to hydrate to produce C-S-H, ettringite and $Ca(OH)_2$. Due to the activation by $Ca(OH)_2$ and sulphate ions, GGBFS is dissolved and then reacts back with $Ca(OH)_2$ and sulphate ions, resulting in the formation of more and more hydration products known as ettringite and C-S-H [26]. The C-S-H formation is also quite important in the strength development of this binder mixture at an early age and late age.

3.4. Workability and Compressive Strength of Super Sulphated Cement Based Concrete

The slump results of 9 concrete mixtures using a binder with high sulphate content are shown in Figure 13.

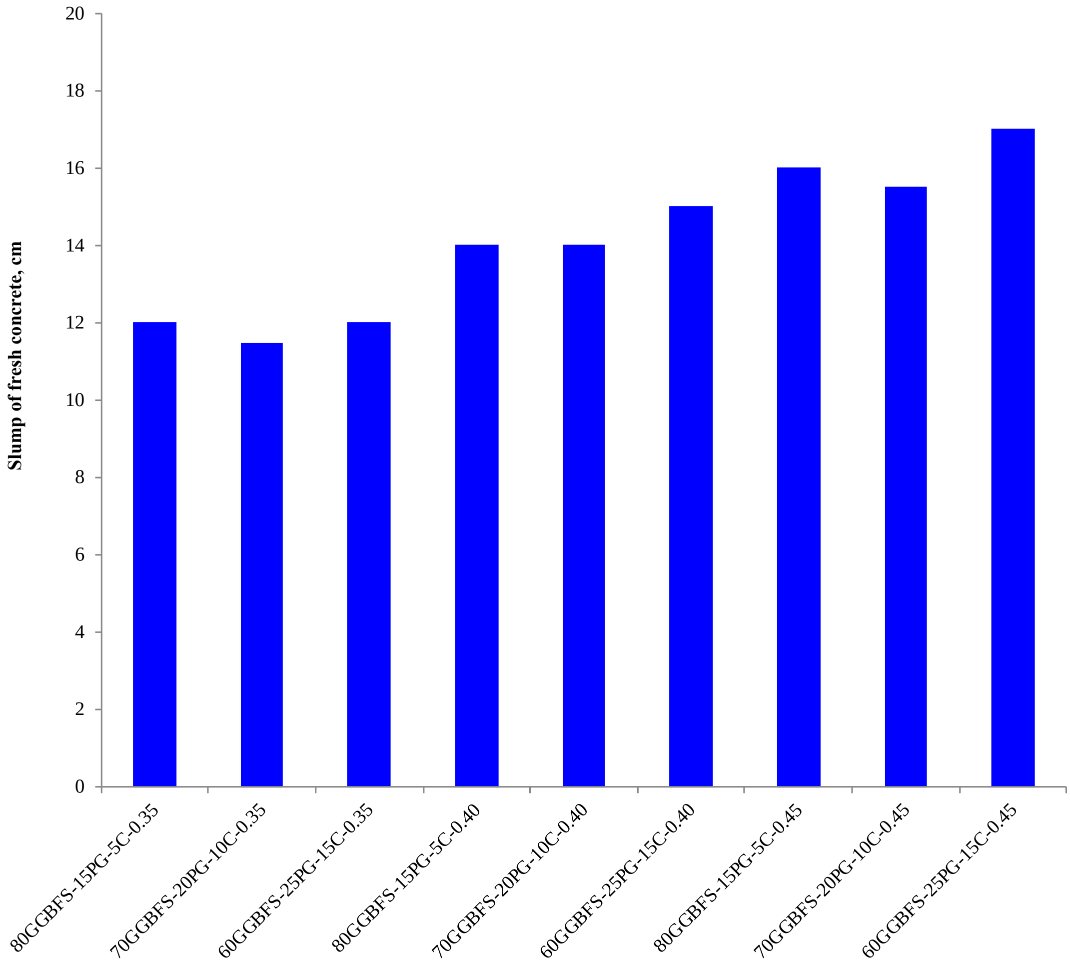

Figure 13. Slump of concrete mixture using super sulphated cement

The slump test results of all concrete mixture show that the increase of the W/B ratio leads to an increase in the slump value for all compositions. At the same W/B ratio, the slump of concrete varies slightly from 11.0 cm to 12.0 cm (with W/B = 0.35), from 14.0 cm to 15.0 cm (with W/B = 0.35). 0.40) and 15.5 cm to 17.0 cm (with W/B = 0.45). The workability of the concrete mixture is relatively good, meeting the construction needs in actual production and application.

The development of compressive strength of concrete at the ratio W/B = 0.35, 0.40 and 0.45 is presented in Figures 14 to 16.

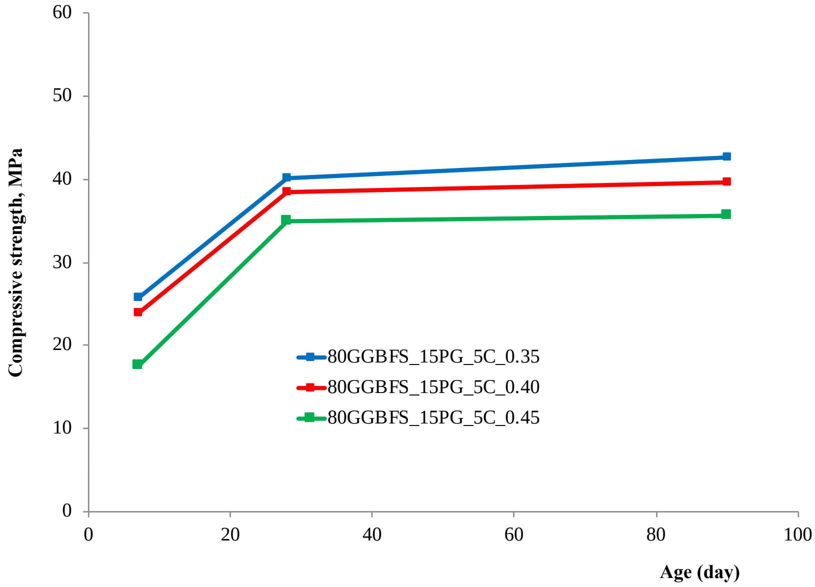

Figure 14. Compressive strength of concrete mixture using composition GGBFS:PG:C = 80:15:5 over time

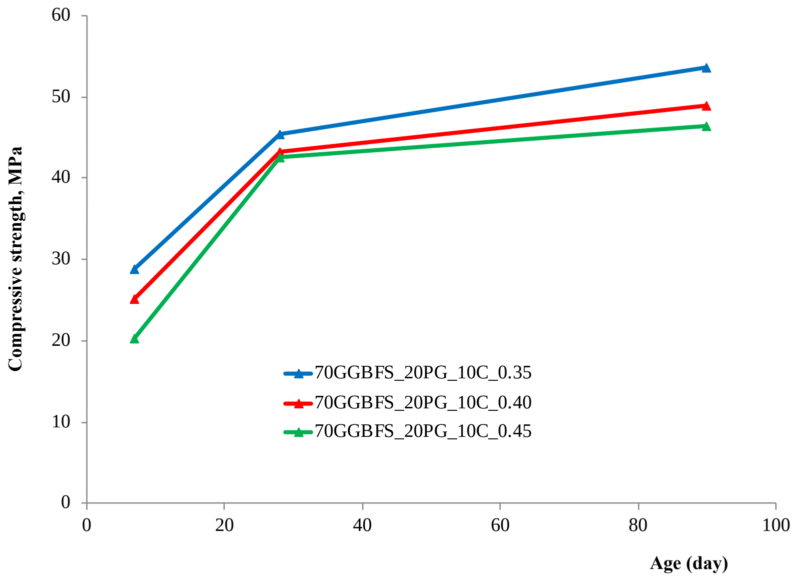

Figure 15. Compressive strength of concrete mixture using composition GGBFS:PG:C = 70:20:10 over time

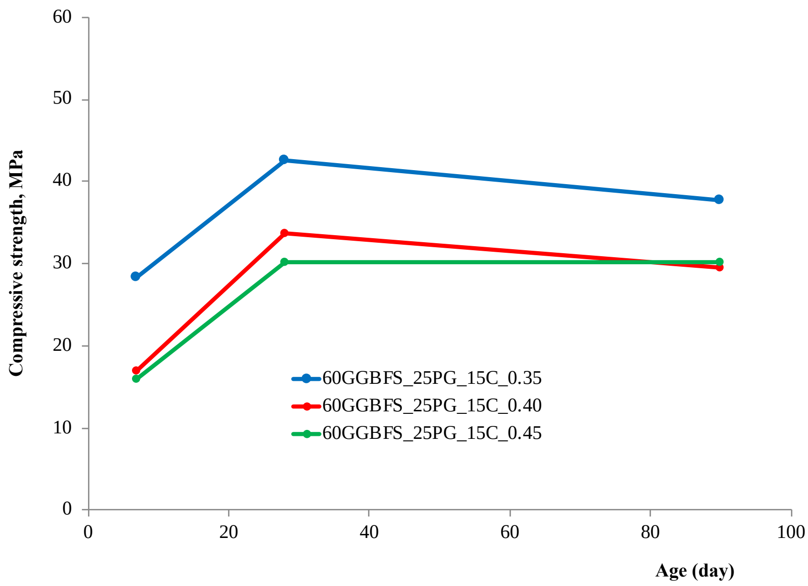

Figure 16. Compressive strength of concrete mixture using composition GGBFS:PG:C = 60:25:15 over time

From the above figures, it is easy to see that as the ratio of W/B decreases, the concrete strength increases. The concrete strength develops rapidly from 7 to 28 days and slows down. The strength of concrete samples at 90 days increased from 15 to 20% for the composition using 5% cement, while the increase was almost negligible for the sample containing 10% cement. Meanwhile, the concrete sample using 15% cement decreases strength at 90 days for all compositions.

The W/B ratio significantly influences the compressive strength, while the difference in compressive strength of different blends with the same W/B ratio is relatively small. The replacement of cement with phosphogypsum leads to a sharp decrease in compressive strength. Phosphogypsum is not a pozzolanic material. For that reason, GGBFS enhances compressive strength as the filler and pozzolanic materials; Meanwhile, the role of the PG is to fill and activate the GGBFS. The proportion of binder used for eco-concrete is 70% PG; 15% GGBFS and 15% PC can be considered as possible optimal replacements for cement by SSC. However, in conventional concrete structures, the concrete strength ranges from 20 to 40 MPa. Therefore, depending on the compressive strength, a suitable cement content can be used in the SSC binder with an appropriate W/B ratio of 0.325.

3.5. Effect of Waste Phosphogypsum Content on Compressive Strength of Concrete

The influence of the content of phosphogypsum waste on the compressive strength of concrete using super sulphated cement is presented in Figures 17 to 19. Experimental results showed that the 28-day compressive strengths of the SSC-based concrete can reach over 40 MPa, which can be found in previous studies [37, 38].

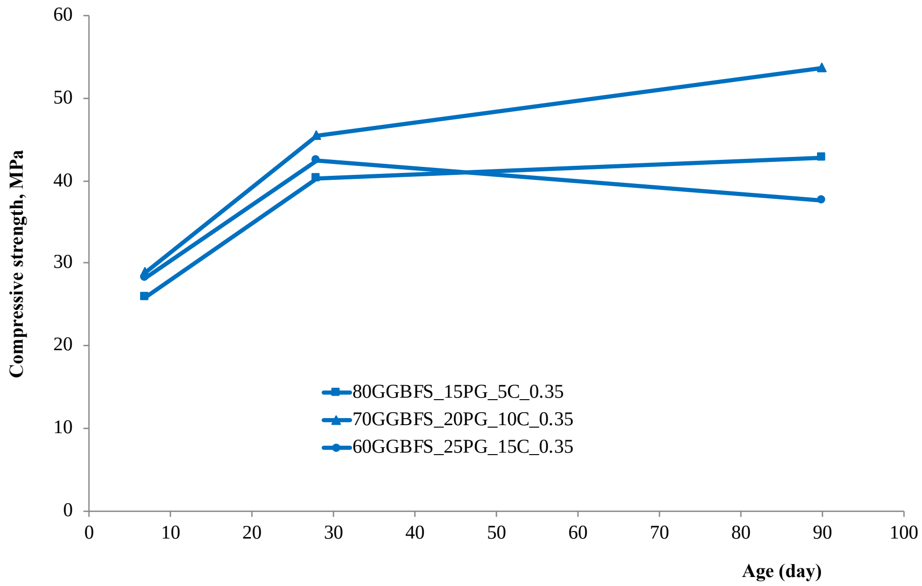

Figure 17. Compressive strength of concrete samples with ratio W/B=0.35 over time

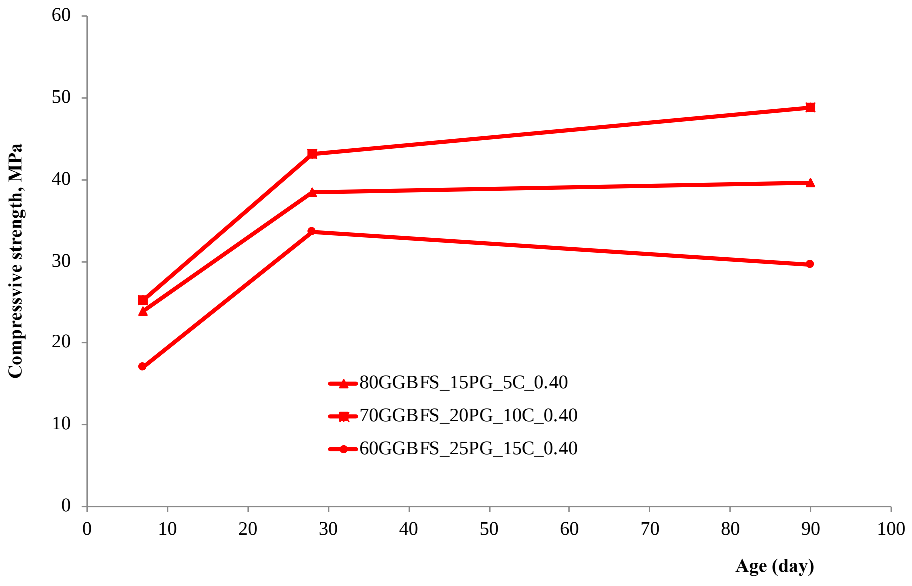

Figure 18. Compressive strength of concrete samples with ratio W/B=0.40 over time

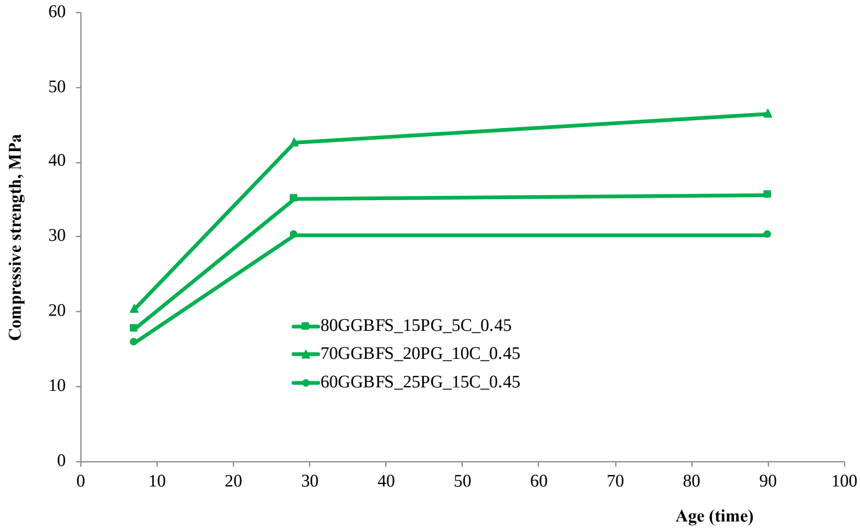

Figure 19. Compressive strength of concrete samples with ratio W/B=0.45 over time

The above results show that when the PG content increases or the slag content decreases, the strength of the concrete samples decreases. Significantly, the compositions with the proportion of GGBFS:PG:C = 60:25:15 have a decline in strength between the ages of 28 and 90 days. This phenomenon occurs when slag, PG, and cement react with each other. It will produce the ettringite, which tends to expand to high volumes. The more the content of PG and cement increases, the more ettringite is formed, which causes more concrete cracking. Therefore, when increasing the PG content, we should reduce the cement content, and vice versa.

4. Conclusions

Based on materials used and experimental conditions performed, the study makes the following conclusions:

- The study has made a binder with high sulphate content from phosphogypsum waste and ground granulated blast furnace slag; the highest compressive strength reaches 66 MPa at 28 days. The activator Na_2CO_3 has overcome the disadvantage of the slow setting of this binder. The setting time meets the requirements of the cement used in construction;
- The use of Na_2CO_3 increases the hardening rate at an early age but also has the potential to reduce the strength of the composite binder at a long age. However, the strength reduction is not much when using 3% Na_2CO_3. The optimal Na_2CO_3 content is about 3%;
- The highest compressive strength belonged to the 70GGBFS-20PG-10C composition. In order to gain high compressive strength for concrete, the waste gypsum content can be up to 15%;
- The main ingredient in the SCC is industrial waste; the amount of cement used is minimal (from 5 to 15 %). Therefore, the research results meet the urgent requirements of developing green materials in the context of increasing industrial waste. On the other hand, using most of the waste in manufacturing binders has excellent environmental significance for sustainable environmental protection;
- Some important technical properties such as shrinkage, sulphate resistance and an improvement to the high-performances concrete will need to be studied in future works.

5. Declarations

5.1. Author Contributions Statement

Conceptualization, N.N.L. and V.P.L.; methodology, V.P.L.; formal analysis, N.N.L. and V.P.L.; investigation, N.N.L.; data curation, N.N.L.; writing—original draft preparation, N.N.L. and V.P.L.; writing—review and editing, N.N.L. and V.P.L.; funding acquisition, V.P.L. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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