

Article

# Effects of Gypsum and Limestone Powder on Fresh Properties and Compressive Strength of Concrete Containing Ground Granulated Blast Furnace Slag under Different Curing Temperatures

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**Abstract:** Usage of industrial by-products such as ground granulated blast furnace slag (GGBFS), gypsum, and limestone powder have gained prominence in concrete production. It is, therefore, very important to conduct research into the various materials and their attendant influence on properties of concrete at different ambient temperatures. This study focused on the slump, setting time, and compressive strength of concrete with GGBFS at a constant replacement ratio, in which different forms of gypsum, namely anhydrous and di-hydrate gypsum, were also added at different SO<sub>3</sub> contents. Effect of addition of limestone powder was also investigated. The results of the tests indicated that both gypsum and limestone powder when added to a mix proportion containing GGBFS can improve slump and compressive strength of concrete. Anhydrous gypsum produced higher optimum compressive strength as compared with di-hydrate gypsum. An increase in SO<sub>3</sub> content from gypsum contributed to strength development at early ages but reduced its long-term strength. Gypsum added to the mix delayed initial and final setting time. Limestone powder accelerated both initial and final setting times and contributed to increasing compressive strength after one day, thus three to seven days; however, the long-term strength was reduced. Curing temperature of concrete influenced strength development and the time required to remove formwork was determined for different mixtures using “maturity function”.

**Keywords:** ground granulated blast furnace slag; anhydrous gypsum; di-hydrate gypsum; limestone powder; setting time; slump; maturity equation



**Citation:** Gyabaah, G.; Miyazawa, S.; Nito, N. Effects of Gypsum and Limestone Powder on Fresh Properties and Compressive Strength of Concrete Containing Ground Granulated Blast Furnace Slag under Different Curing Temperatures. *Constr. Mater.* **2022**, *2*, 114–126. <https://doi.org/10.3390/constrmater2020009>

Received: 21 March 2022

Accepted: 2 June 2022

Published: 8 June 2022

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## 1. Introduction

Over the years, concrete has dominated the construction industry due to the fact that its constituent materials are evenly distributed throughout the world, thereby making it easily available for use. Cement, which is a major component of concrete, has been used for centuries as a result of the hydraulic property that it possesses. However, the production of cement has drawn a lot of criticisms and concerns due to its contribution towards the release of carbon dioxide into the atmosphere. In 2016, cement production generated around 2.2 billion tons of CO<sub>2</sub>—equivalent to 8% of the global total CO<sub>2</sub> emission [1]. In order to reduce the CO<sub>2</sub> emission footprint in cement production, industrial by-products, also known as supplementary cementitious materials, are introduced in concrete mix proportions to partially replace Portland cement. One of such SCMs is ground granulated blast furnace slag (BFS), which is a by-product from iron or steel production. Alkali-activated materials, in which Portland cement is not used at all, have recently been demonstrated for their environmental-friendly nature [2]. However, it is still difficult to use this type of material as a general-purpose concrete material.

In Japan, a blended cement incorporating BFS at a replacement ratio of around 40%, accounts for 20% of the total amount of cement used and has been earmarked as an environmentally-friendly product [3]. This means the cement with GGBFS is the second popular cement next to ordinary Portland cement in this country. However, the effects of the kind and the contents of minor additives such as gypsum and limestone powder have not been made clear yet.

Gypsum is an important additive that plays a critical role in cement production. The additive ingredient present in gypsum is calcium sulfate. Gypsum exists in many forms, such as anhydrous gypsum, dihydrate gypsum, and hemihydrate, with different solubility rates, which are very important in determining the strength gain and setting of concrete. Hemihydrate has the highest solubility, about five times that of gypsum, while natural anhydrite is the least soluble. The quantity or optimum amount of  $\text{SO}_3$  to be used in concrete need to be specified since it affects not only setting but compressive strength and expansion. The minimum content of  $\text{SO}_3$  required to control setting is typically around 2% [4]. In a study, it was reported that the  $\text{C}_3\text{S}$  reaction amount increased when gypsum was incorporated in a concrete mix containing ggbfs and the increase was thought to have affected the strength enhancement of the mix containing gypsum [5]. Another research studied compressive strength development by adding gypsum and observed that gypsum addition produced fine ettringite crystals and removed large pores, resulting in significant pore-size refinement and enhancing strength development. However, excessive gypsum addition led to a reduction in strength due to expansion [6]. An experiment was conducted to compare compressive strength development using two forms of calcium sulfates, namely natural gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and anhydrite ( $\text{CaSO}_4$ ). The test results indicated that the higher optimum strength was achieved in the mix containing anhydrite as the retarder because it contained less pore volume, lower average pore diameter, and higher solubility [7].

Limestone powder can be used to replace Portland cement in concrete production, and it acts as a filler with some beneficial effects on some concrete properties, such as workability, permeability, etc. Limestone powder mainly consists of calcium carbonates also called calcite and its reaction undergoes three sequences when added to Portland cement: 1. Ettringite forms through consumption of mono-sulphate; 2. When mono-sulphate is exhausted, mono-carbonate forms through consumption of hermi-carbonate; and 3. When the hermi-carbonate phase is used up, additional calcium carbonate does not react but persists as a stable phase [8]. The first two reactions give limestone powder its filler properties while the third reaction makes limestone powder a 'diluent' in that porosity increases due to further addition of carbonates. In Japan, the maximum limestone powder replacement level is 5%. On setting time, a study reported that the addition of limestone powder led to an acceleration of setting time [9,10]. A substantial decrease in initial and final setting time after inter-grounding an additional 5% of limestone with cement clinker containing 5% gypsum has been reported [11]. Limestone powder addition can have both positive and negative effects on compressive strength. Limestone powder was added to a concrete mix containing 20% and 25 wt% BFS and compressive strength was found to increase [12]. At limestone replacements up to 5%, there is an increase in early-age strength as a result of improved particle packing and an increase in cement hydration [13]. When limestone powder addition was 15%, concrete reduced in strength as the limestone content increased [14,15].

The objective of this research is to improve the properties of general-purpose cement with BFS by modifying composition of minor additives. Fresh properties of concrete such as slump, setting time, and compressive strength cast at two different ambient temperatures were experimentally investigated on concrete mixture proportions containing ground granulated blast furnace slag, incorporating two different forms of gypsum, namely anhydrous gypsum and dihydrate gypsum, using variable  $\text{SO}_3$  contents and limestone powder. By curing the mix proportions at two different temperatures of 20 °C and 10 °C, the formwork removal time was also estimated using "maturity equation".

## 2. Materials and Test Methods

### 2.1. Materials

Ordinary Portland cement, herein referred to as “N”, manufactured in accordance with Japanese Industrial Standard, JIS R 5210 [16] was used. Blast furnace slag referred to as “BFS”, produced in conformity with JIS A 6206 [17] was used. Anhydrous gypsum (CS) and di-hydrate gypsum (CSH<sub>2</sub>) conforming to JIS R 9151 [18] and limestone powder (LSP) were also used. The chemical and physical properties of the cementitious materials are presented in Tables 1 and 2, respectively.

**Table 1.** Chemical composition of cementitious materials.

Cementitious Materials	Chemical Composition (%)											
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	Ig-Loss
N	20.99	5.37	3.07	64.08	1.94	2.16	0.39	0.35	0.29	0.49	0.06	0.77
BFS	34.07	14.77	0.34	42.07	6.27	-	0.18	0.37	0.65	0.02	0.28	0.16
CS	1.00	0.30	0.10	40.40	0.10	57.10	-	-	-	-	-	0.90
CSH <sub>2</sub>	-	-	-	31.90	-	45.60	-	-	-	-	-	20.50
LSP	-	0.12	-	55.30	0.23	0.01	-	-	-	-	-	43.40

**Table 2.** Physical properties of cementitious materials and aggregates.

Material	Density (g/cm <sup>3</sup> )	Blaine Fineness (cm <sup>2</sup> /g)	Absorption (%)	Fineness Modulus
N	3.16	3220	-	-
BFS	2.90	4460	-	-
CS	2.90	3610	-	-
CSH <sub>2</sub>	2.31	8930	-	-
LSP	2.71	7190	-	-
Sandstone	2.62	-	0.76	-
River sand	2.60	-	2.11	2.75

Fine aggregate used in this study was river sand obtained from the Kinugawa River in Japan. The coarse aggregate used was crushed sandstone from Kuzu in Japan. Two gradations of crushed sandstone with particle sizes of 5–13 mm and 13–20 mm were used in a mix ratio of 1:1. Table 2 shows the physical properties of the aggregates.

### 2.2. Binder Composition and Mixing Proportion

In this study, ten (10) mixture proportions were prepared. Six (6) of them were cast in autumn (November) and the specimens were kept in water of 20 °C. Four out of the six mix proportions were selected and cast in winter (January) and the specimens were then kept in water of 10 °C. The percentage composition of the binders in the concrete by mass can be seen in Figure 1. The replacement ratio of BFS in all concrete mix proportions was kept constant at 40%wt of cement (N). The reason was to make sure the replacement ratio was consistent with the typical replacement levels of 40–45% when BFS is used in Japan. The composition of N(58)BFS(40)CS(2) corresponds to that of the typical blast-furnace slag cement commercially available in Japan. The SO<sub>3</sub> content of CS were varied using replacement ratios of 2% and 4%, while the SO<sub>3</sub> content of CSH<sub>2</sub> was kept at 4%. LSP was used to replace 5%wt of the cement. The water–binder (w/b) ratio was kept constant at 0.5 for all the mix proportions. Tables 3 and 4 summarize the mixture proportions of the concrete samples at curing conditions of 20 °C and 10 °C, respectively. Air-entraining (AE) agent and an air-entraining water reducing (AEWR) admixture in conformity with JIS A 6204 [19] were added to the mixes to entrain air and improve workability. The dosage of AEWR was kept constant at 1.0% according to the manufacturer’s instructions while that of AE was varied to meet the target air content value.

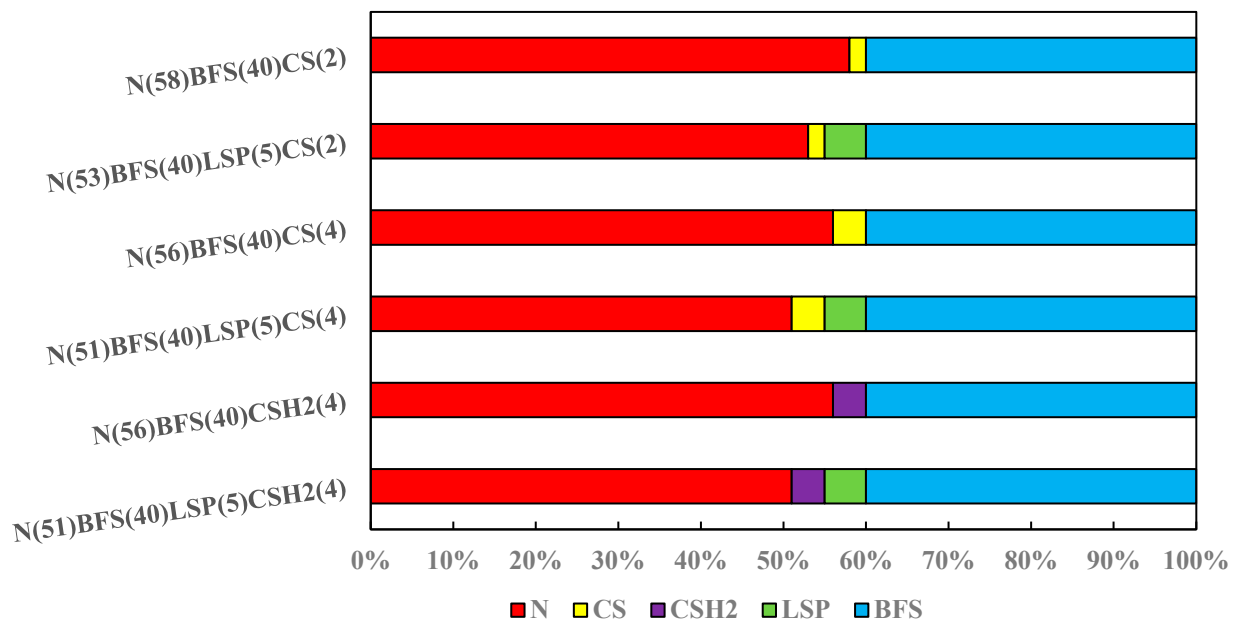


Figure 1. Percentage composition of binders in concrete by mass.

Table 3. Mix proportion of concrete cast in autumn and cured at 20 °C.

Mix. Proportion	W/B (%)	S/a (%)	Unit Weight (Kg/m <sup>3</sup> )				Chemical Admixture	
			Water	B	S	G	AEWR (%)	AE (%)
N(58)BFS(40)CS(2)					829	942		0.0006
N(53)BFS(40)LSP(5)CS(2)					828	941		0.0011
N(56)BFS(40)CS(4)					828	942		0.0006
N(51)BFS(40)LSP(5)CS(4)	50	47	167	334.0	828	940	1.0	0.0011
N(56)BFS(40)CSH <sub>2</sub> (4)					826	939		0.0006
N(51)BFS(40)LSP(5)CSH <sub>2</sub> (4)					825	938		0.0008

a: aggregate; S: Fine aggregate (River sand); G: Coarse aggregate (Sandstone); B: binder.

Table 4. Mix proportion of concrete cast in winter and cured at 10 °C.

Mix. Proportion	W/B (%)	S/a (%)	Unit Weight (Kg/m <sup>3</sup> )				Chemical Admixture	
			Water	B	S	G	AEWR (B%)	AE (B%)
N(58)BFS(40)CS(2)					829	942		0.0006
N(53)BFS(40)LSP(5)CS(2)					828	941		0.0008
N(51)BFS(40)LSP(5)CS(4)	50	47	167	334.0	828	940	1.0	0.0008
N(51)BFS(40)LSP(5)CSH <sub>2</sub> (4)					825	938		0.0006

a: aggregate; S: Fine aggregate (River sand); G: Coarse aggregate (Sandstone); B: binder.

### 2.3. Test Methods and Specimen Preparation

A pan-type concrete mixer with a total capacity of 60 L was used. Mixing was done for 3 min before discharging into a collecting trough for slump, air content, setting time, and compressive strength cylinder specimen test to be done.

Slump test conducted was in accordance with JIS A 1101 [20], which is similar to ASTM C143 [21]. By using Abram’s slump cone, its interior surface as well as the surface of the metal base plate were dampened with water. The cone was held firmly down against the metal plate and filled with concrete in three layers with each layer being rodded 25 times using a tapping rod. Excess concrete at the top of the cone was removed and flattened to obtain the exact height of the cone. The cone was slowly and carefully lifted vertically from the concrete. The slump was recorded as the difference between the height of the mold and the height of the subsided concrete from its center. The air content test also done conformed to JIS A 1128 [22] and ASTM C231 [23]. Using a pressure meter, concrete was collected and

placed in the bowl in three layers of equal volume with each layer rodded 25 times. The sides of the container were struck 10–15 times using a mallet to remove air and compact concrete for each layer. Excess concrete was struck off until it was smooth on top of the bowl at rim level. The cover was attached to the bowl after cleaning the edges of the rim. Water was squeezed into the bowl using a syringe through the pouring hole while the petcocks on the air meter remained open and later closed as the poured water began to come out from the end of the other valve. Air was pumped using the handpump on the air meter. The regulating valve was gradually opened until the pressure gauge pointer aligned itself exactly with the initial pressure mark. By using the lever, the pressure in the measuring bowl was released and the sides of the gauge were lightly tapped using the finger until the pressure stabilized. The reading at this point was recorded as the apparent air content of the concrete in percentage. Setting time test was carried out as specified in JIS A 1147 [24] and ASTM C403 [25]. In this test, mortar specimen was prepared by randomly collecting concrete from the mixture under the test and sieved using a 4.75 mm sieve. The mortar was placed in a cylindrical container and kept in a temperature and humidity-controlled room. The specimen was checked regularly to determine the beginning of stiffness and any bleed water that had accumulated on the top surface was removed. For initial penetration, the mortar specimen was placed under the bearing surface of a 11 mm diameter penetration needle and a vertical force was applied at a constant speed. Random penetration resistance measurements were made at randomly chosen time intervals until a pressure value of 0.35 kN was reached and the needle was changed to mark the end of initial set. A second needle with a diameter of 5.5 mm was used for the final set and care was taken to avoid areas where the mortar had been disturbed by previous test. The same procedure was repeated at randomly selected time intervals until the pressure value reached 0.70 kN. Specimens for compressive strength tests were prepared in accordance with JIS A 1108 [26] and ASTM C39/C39M [27] using cylindrical molds measuring  $\phi 100$  mm  $\times$  200 mm height. Cylindrical specimens were kept in a temperature-controlled room and demolded after 24 h and then immersed in a curing water of 20 °C and 10 °C. Compressive strength test was carried out at 1, 3, 7, 28, and 91 days. Three specimens were prepared for each test age and crushed under a compression testing machine at a loading rate of 2 kN/s.

### 3. Experimental Results and Discussions

#### 3.1. Slump

Table 5 shows the results of slump test for the various mix proportions cast at two different ambient temperatures while keeping the water content and AEW dosage constant. In mix N(58)BFS(40)CS(2), the slump was higher when the casting temperature was 20 °C as compared with 10 °C at the same A.E dosage of 0.0006%. In fact, even though there was a slight variation in the A.E dosage, slump results attained for the same mixes were higher at 20 °C than at 10 °C. Moreover, when the SO<sub>3</sub> content in gypsum was increased from 2% to 4%, the slump increased from 11.2 cm to 14.7 cm. This indicates that increasing SO<sub>3</sub> content leads to an improvement in slump. This is because gypsum as a retarding agent retards hydration of aluminate phases and slows the formation of calcium aluminate hydrates, which allows a high amount of water available during early hydration, thus improving workability [28]. Using two different forms of gypsum with the same SO<sub>3</sub> content, it can be observed that a higher slump value was obtained in the mix containing di-hydrate gypsum, thus, N(56)BFS(40)CSH<sub>2</sub>(4) as compared with that of anhydrous gypsum, N(56)BFS(40)CS(4). The reason is that di-hydrate gypsum contains more water and as result to higher workability in concrete. Furthermore, where LSP was added to a mix proportion, slump also increased but with a slight increase in A.E dosage at the two different casting temperatures.

#### 3.2. Setting Time

Table 6 and Figure 2 show the results of setting time among four mix proportions. Setting time test was carried out on four mix proportions in a temperature and humidity-

controlled room of 20 °C and 80%, respectively. The results indicate that the addition of gypsum in concrete leads to a retardation in both initial and final setting time of concrete as seen in mix N(58)BFS(40)CS(2). However, an increase in SO<sub>3</sub> content in gypsum did not have any significant influence on initial setting time of concrete as can be seen from mixes N(53)BFS(40)LSP(5)CS(2) and N(51)BFS(40)LSP(5)CS(4). This is in agreement with Taylor that, “the minimum content of SO<sub>3</sub> required to control setting is typically around 2% and so any further increase in SO<sub>3</sub> content beyond the minimum required has little effect on setting unless the proportion of hemihydrate or soluble anhydrite is so high as to cause false set” [29]. For all mixes containing LSP, initial setting time occurred at a quicker rate because LSP accelerates setting time. By changing the form of gypsum, initial setting time accelerated quickly in mix N(51)BFS(40)LSP(5)CSH<sub>2</sub>(4) as compared with N(51)BFS(40)LSP(5)CS(4) despite the SO<sub>3</sub> content being the same. This is because CSH<sub>2</sub> has a lower solubility rate that does not allow it to supply sulfate ions quickly to prevent early hydration of C<sub>3</sub>A, which leads to the faster initial setting. The initial set times recorded by mixes N(58)BFS(40)CS(2) and N(51)BFS(40)LSP(5)CSH<sub>2</sub>(4) varied significantly because CS in the former mix delayed initial setting time due to its role as a set retarder, while LSP and CSH<sub>2</sub> in the latter mix reduced the initial setting time as a result of their roles as set accelerators. However, the final set times of both mixes were almost attained at the same time.

**Table 5.** Test results of fresh concrete at different casting ambient temperatures.

Mix Proportion	20 °C		10 °C	
	Slump (cm)	Air Content (%)	Slump (cm)	Air Content (%)
N(58)BFS(40)CS(2)	11.2	3.2	9.0	4.1
N(53)BFS(40)LSP(5)CS(2)	12.8	4.3	9.7	3.9
N(56)BFS(40)CS(4)	14.7	4.4	-	-
N(51)BFS(40)LSP(5)CS(4)	16.7	5.4	13.0	4.0
N(56)BFS(40)CSH <sub>2</sub> (4)	17.0	4.9	-	-
N(51)BFS(40)LSP(5)CSH <sub>2</sub> (4)	16.1	5.3	15.4	4.1

**Table 6.** Elapsed setting time of mix proportions.

Mix Proportion	Setting Time (h)		
	Initial Set	Final Set	Elapsed Time
N(58)BFS(40)CS(2)	7.65	11.20	3.55
N(53)BFS(40)LSP(5)CS(2)	7.15	10.32	3.17
N(51)BFS(40)LSP(5)CS(4)	7.15	11.03	3.88
N(51)BFS(40)LSP(5)CSH <sub>2</sub> (4)	6.66	11.17	4.51

### 3.3. Compressive Strength

Compressive strength was calculated as the average of three samples crushed under a compression testing machine. Due to the low strength at one day, the top surface was capped using an unbonded cap of diameter 102 mm to provide the even surface needed. Figure 3 summarizes the combined effects of all the binder materials on compressive strength at each day. This is an indication that as time progresses and hydration continues to occur, each binder contributes to strength development, hence the variation in strength among the mixture proportions. Therefore, the effects of the binder materials are explained in the subsequent figures.

Figure 4 shows the effect of LSP addition on compressive strength of concrete. The results indicate that at one day, LSP did not contribute to strength development. This observation is in agreement with other research that LSP is less reactive, and its reactivity starts after about one day and the extent of such reactivity is controlled by the amount of sulfate in the system [30]. However, after one day, mix N(58)BFS(40)CS(2) attained a higher strength at three, seven, and 28 days in comparison with N(53)BFS(40)LSP(5)CS(2). This is due to nucleation effect and also after about one day, LSP starts to react after the initial calcium sulfate is consumed and the formed ettringite phase begins to convert

to AFm phases to form carbo-aluminate (hemi, mono carbo aluminate hydrates), which fills the pores and enhances increase in strength [30]. However, at age 91, there was a decrease in strength in mix N(53)BFS(40)LSP(5)CS(2). This is because not all the LSP reacts and, therefore, acts as a diluent that increases porosity of the concrete, thereby reducing its strength. Presented in Figure 5 is the influence of SO<sub>3</sub> content in gypsum on concrete’s compressive strength. It is observed that the strength was slightly higher in mix N(56)BFS(40)CS(4) at one, three, and seven days compared with mix N(58)BFS(40)CS(2). This can be attributed to the fact that, at early ages where more gypsum is consumed, there is an increase in the rate of hydration and the release of more sulfate ions, which accelerates the hydration of C<sub>3</sub>S and an increase in compressive strength. At 28 days, strength in both mixes were similar but at 91 days, N(56)BFS(40)CS(4) achieved a reduction in strength because the C-S-H gel formed at the early hydration stage due to increased SO<sub>3</sub> content was inferior in quality and led to more pores and expansion, which affected its later strength.

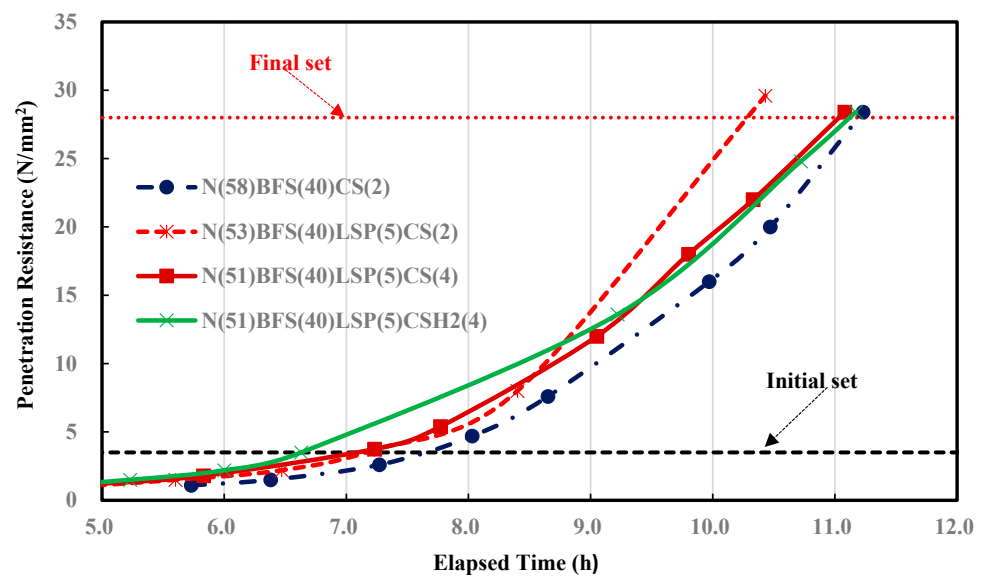


Figure 2. Setting time test results.

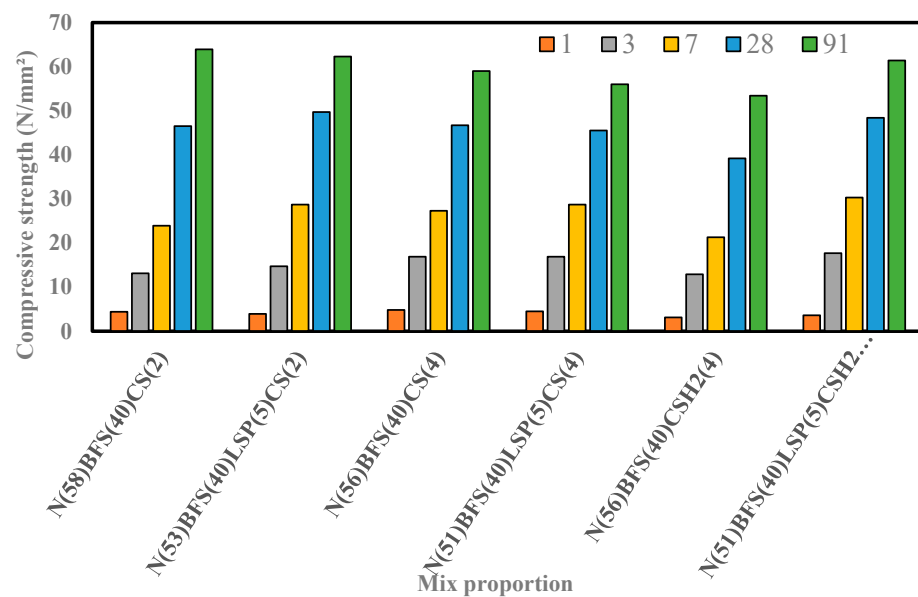


Figure 3. Combined effects of binder materials on compressive strength.

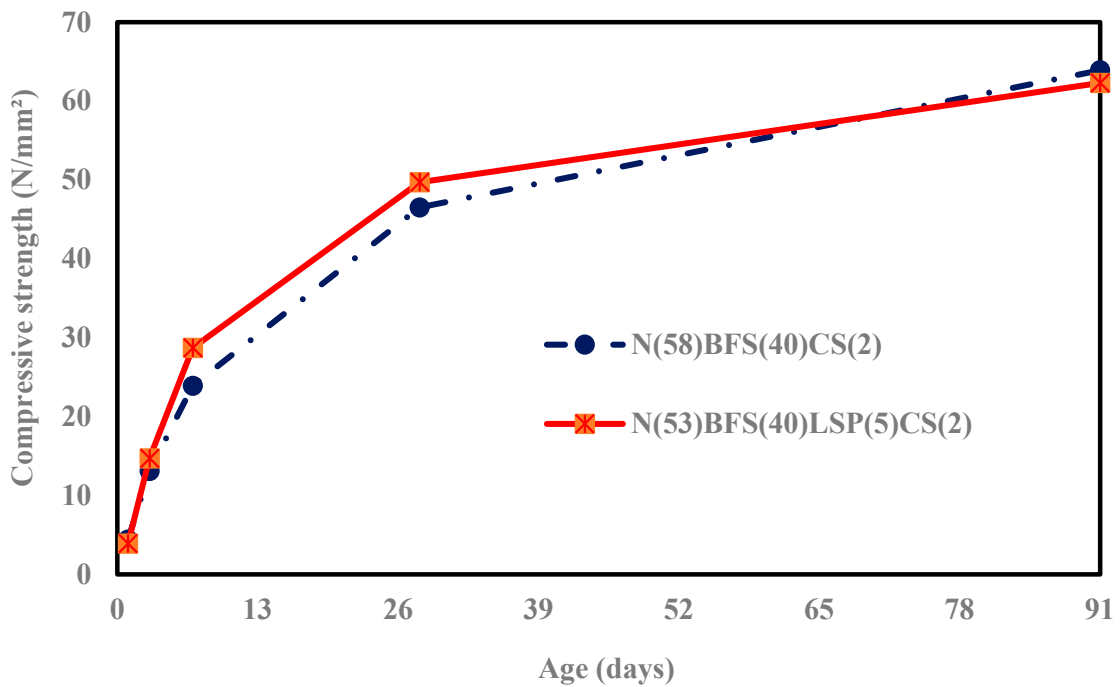


Figure 4. Effect of LSP on compressive strength.

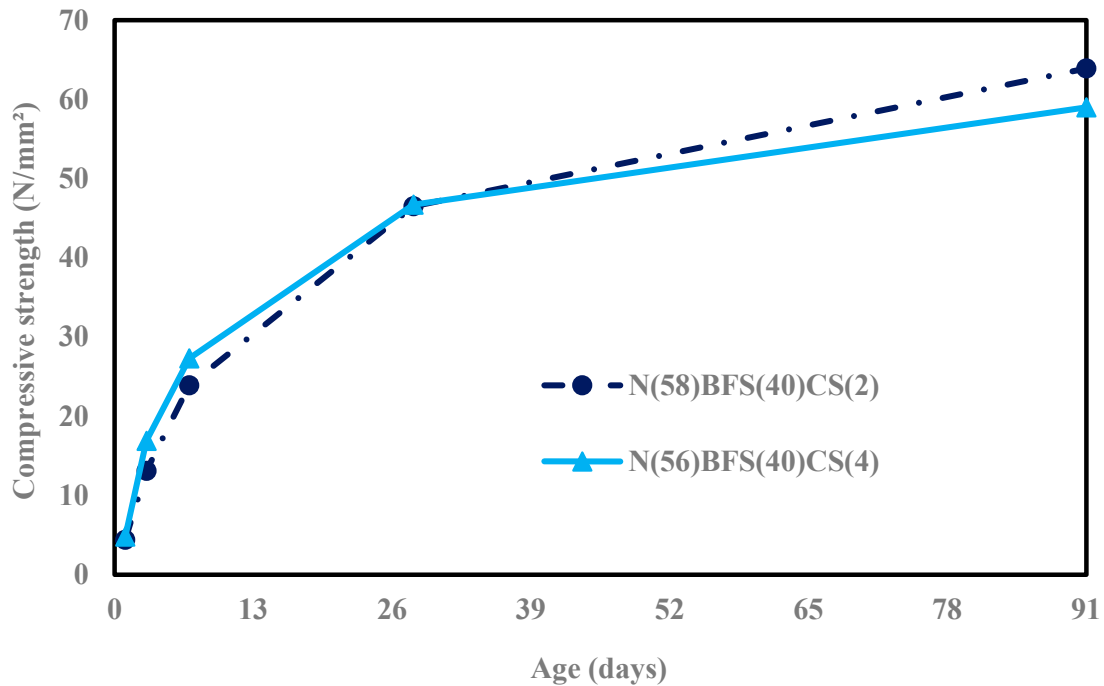


Figure 5. Effect of SO<sub>3</sub> content in gypsum on compressive strength.

The results of the type or form of gypsum on compressive strength can be seen in Figure 6. Higher compressive strength was achieved at all ages in the mix containing anhydrous gypsum (CS), thus N(56)BFS(40)CS(4), than that of the di-hydrate gypsum (CSH<sub>2</sub>), as in mix N(56)BFS(40)CSH<sub>2</sub>(4). CS has a higher solubility rate and, therefore, releases sulfate ions quickly and in greater quantities that prevents tricalcium aluminates (C<sub>3</sub>A) from early reaction but in turn accelerates tricalcium silicates (C<sub>3</sub>S) hydration, which generates more calcium-silicate-hydrate (C-S-H), which results in higher compressive strength [29]. Numerical approaches to estimate the effect of additives on compressive strength of concrete have been reported [31]. In the present study, however, the dosages



of minor additives were set within narrow ranges according to the Japanese standard for blast-furnace slag cement [17]. So, in order to quantitatively estimate the effects of minor additives on compressive strength of concrete, more experiments should be carried out for mixtures with wider dosages of minor additives.

#### 3.4. Effect of Curing Temperature on Compressive Strength

In the construction of concrete structures, an idea on concrete strength development is very important to enable contractors, engineers, and technicians to determine formwork removal time and application of construction loads for safety and expediency. The easiest and simplest approach is the use of the “maturity method”. In this technique, in-situ concrete strength can be predicted or estimated using temperature and time history of the concrete.

The “maturity function” results were analyzed using the compressive strength development data of four mixture proportions that were moist cured in two different curing conditions of 20 °C and 10 °C. A graph indicating log of maturity index on the  $x$ -axis and concrete compressive strength on  $y$ -axis was plotted. The maturity index (MI) was calculated using the Nurse-Saul function [32,33], given below as

$$M = \sum_0^t (T_a - T_o) \Delta t \quad (1)$$

where:  $M$  = maturity index (°C-hours or °C-days),  $T_a$  = average concrete temperature (°C) during the time interval  $\Delta t$ ,  $T_o$  = datum temperature (usually taken to be  $-10$  °C),  $t$  = elapsed time (hours or days), and  $\Delta t$  = time interval (hours or days).

From the results of the graph, a linear regression relationship indicating temperature and compressive strength up to 91 days was determined. Figure 7a–d shows the linear regression for each mix proportion at the two curing conditions of 20 °C and 10 °C and the equations for estimating or predicting the in-situ concrete strength. Compressive strength was higher at all ages when cured at 20 °C than at 10 °C. This shows that compressive strength of concrete depends on curing temperature for continuous strength gain. Compressive strength also gives an indication on the appropriate time to remove formwork to ensure the safe application of construction loads and speed. The “maturity function” was, therefore, used to predict the time for which each mix proportion could attain a strength of 10 N/mm<sup>2</sup> under the two curing temperatures. JASS 5 [34] specifies a strength of either 5 N/mm<sup>2</sup> or 10 N/mm<sup>2</sup> as sufficient for formwork removal depending on the planned service period of the structure and in this study 10 N/mm<sup>2</sup> was chosen. From Table 7, it can be observed that all the mix proportions cured at 20 °C attained a quicker formwork removal time (days) than when cured at 10 °C. Mix N(51)BFS(40)LSP(5)CS(4) achieved the quickest days for formwork removal in 1.4 days followed by both N(53)BFS(40)LSP(5)CS(2) and N(51)BFS(40)LSP(5)CSH<sub>2</sub>(4) at 1.7 days. Mix N(58)BFS(40)CS(2) took the most days to achieve the same strength for formwork removal in 2.2 days and 4.2 days at 20 °C and at 10 °C, respectively. It can be inferred from Table 7 that addition of additives such as LSP can accelerate formwork removal time for concrete containing BFS. This indicates that even though the binder materials and contents were the same, curing temperature played a significant role in determining the stripping time for formwork.

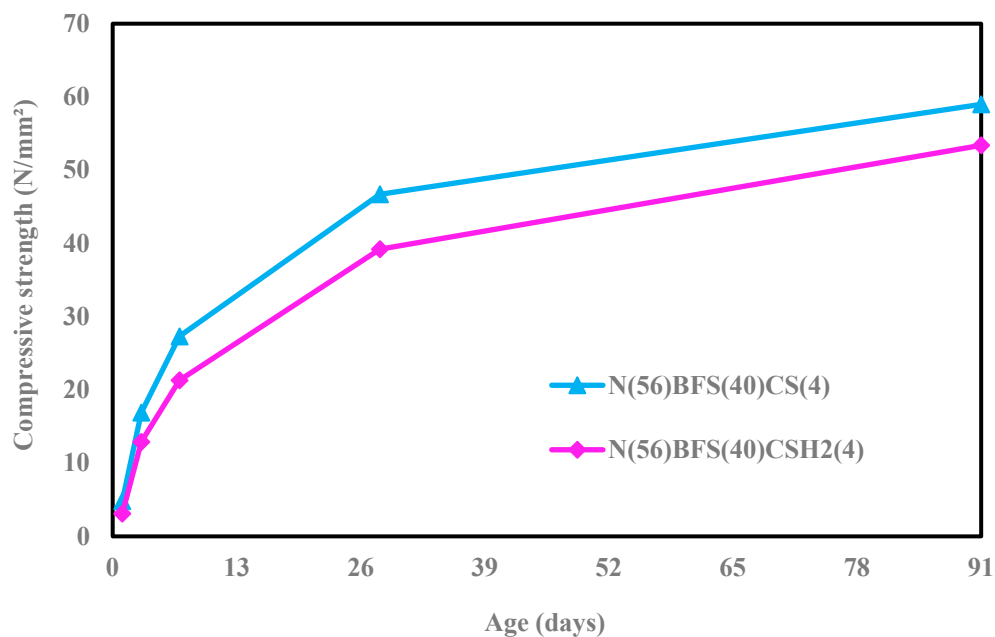


Figure 6. Effect of type or form of gypsum on compressive strength.

Table 7. Age of concrete to obtain compressive strength of 10 N/mm<sup>2</sup> for formwork removal.

Mix Proportion	Curing Temperature (°C)	
	20	10
Age of Concrete (Days)		
N(58)BFS(40)CS(2)	2.2	4.2
N(53)BFS(40)LSP(5)CS(2)	1.7	3.3
N(51)BFS(40)LSP(5)CS(4)	1.4	3.3
N(51)BFS(40)LSP(5)CSH <sub>2</sub> (4)	1.7	3.3

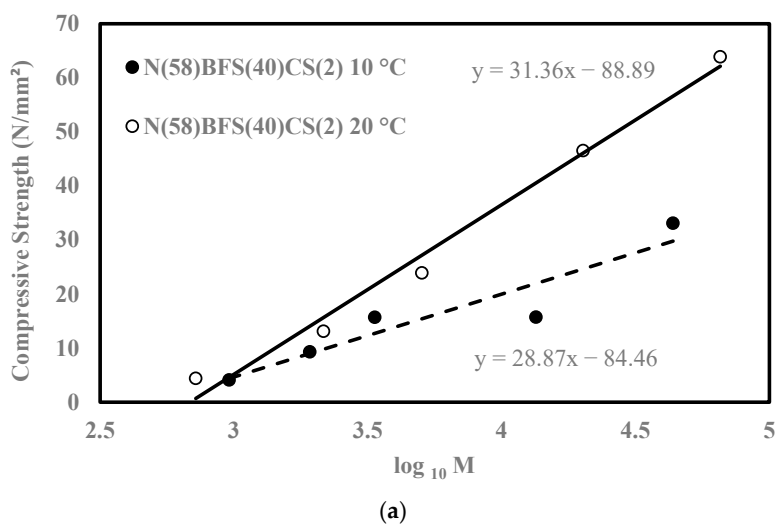
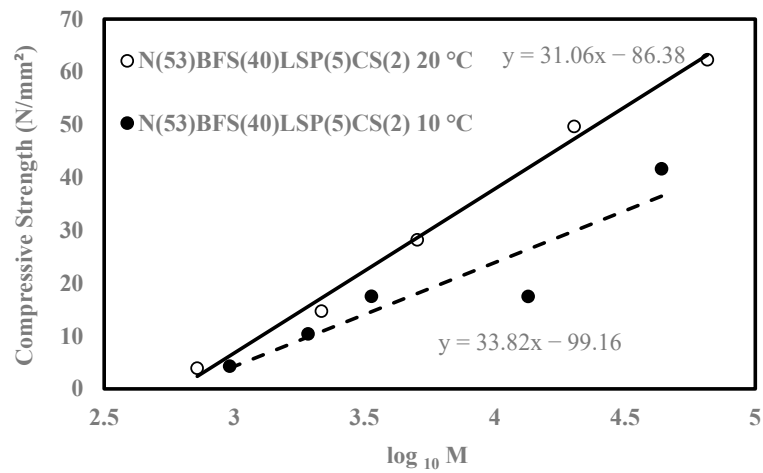
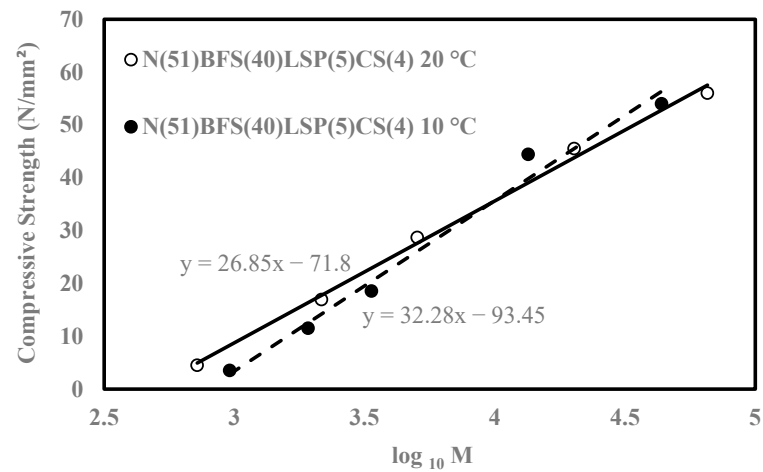


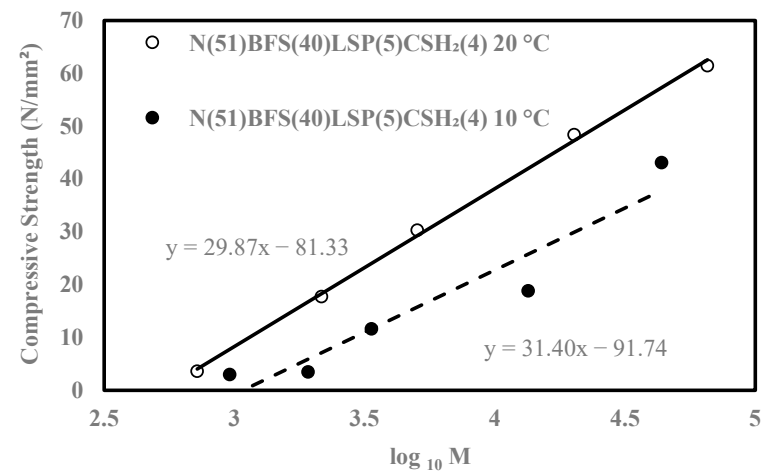
Figure 7. Cont.



(b)



(c)



(d)

**Figure 7.** Results of compressive strength plotted against log of maturity index for mix proportions at curing temperature conditions of 20 °C and 10 °C. (a) Compressive strength versus log of maturity index for mix N(58)BFS(40)CS(2); (b) Compressive strength versus log of maturity index for mix N(53)BFS(40)LSP(5)CS(2); (c) Compressive strength versus log of maturity index for mix N(51)BFS(40)LSP(5)CS(4); (d) Compressive strength versus log of maturity index for mix N(51)BFS(40)LSP(5)CSH<sub>2</sub>(4).

#### 4. Conclusions

The study evaluated the influences of anhydrous gypsum, di-hydrate gypsum, and limestone powder on fresh properties and compressive strength of concrete with ground granulated blast-furnace slag and the effect of curing temperature on formwork removal time. The following deductions were made:

- (1) LSP addition led to an acceleration in both initial and final set times due to increase in hydration caused by nucleation effect. Gypsum, CS, on the other hand, led to a significant retardation in both initial and final set times of concrete because it is a retarder. Increase in SO<sub>3</sub> content in gypsum did not have any significant effect on initial set time of concrete. Di-hydrate gypsum attained a quicker initial set time than anhydrous gypsum due to its lower solubility rate.
- (2) The compressive strength of concrete can be improved in a mix proportion containing BFS by adding LSP.
- (3) The addition of gypsum to concrete containing BFS results in an increase in compressive strength. Moreover, compressive strength was higher when anhydrous gypsum, CS, was added to mix proportion in comparison with a mix containing di-hydrate gypsum, CSH<sub>2</sub>, which can be attributed to the faster solubility rate of anhydrous gypsum, which promotes quick reaction of tricalcium silicates that facilitates strength enhancement.
- (4) Increasing the SO<sub>3</sub> content in gypsum from 2% to 4% led to an increase in compressive strength at early ages (one to seven days); however, at a later age (91 days), compressive strength reduced when SO<sub>3</sub> was higher.
- (5) Curing temperature greatly affects compressive strength development and formwork removal time. Additives such as LSP can be added to concrete containing BFS to accelerate formwork removal time.

**Author Contributions:** Initial conceptualization, G.G. and S.M.; further modification of initial conceptualization, S.M. and N.N.; Chemical analysis of cementitious materials, N.N.; laboratory work, data analysis and interpretation, G.G. and S.M.; writing of original draft, G.G.; review and editing of original draft, S.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to non-agreement by the authors in order to prevent it from being re-used.

**Acknowledgments:** This research was ably supported by the Civil and Environmental Engineering Department of Ashikaga University, Japan with technical assistance from the Technical Department of DC. Co., Ltd., Japan. The authors will also like to express their sincere gratitude to Japan international Cooperation agency (JICA) through whose Africa Business Educative Initiative (ABE) scholarship, the first author was awarded to undertake research in Japan.

**Conflicts of Interest:** The authors declare no conflict of interest.

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