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The Influence and Application of Slag, Fly Ash, and Limestone Flour on Compressive Strength of Concrete Based on the Concrete Compressive Strength Development over Time (CCSDOT) Model

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Featured Application: The influence and application of supplementary cementitious materials on concrete compressive strength.

Abstract: Concrete and cement have been widely used in past decades as a result of urbanization. More and more supplementary cementitious materials are adopted in concrete because its production complements environmental conservation. The influence of slag, fly ash, limestone, etc., on compressive strength of concrete is of interest to engineers worldwide. Many previous studies were specific to certain engineering or certain experiments that could not reveal the nature of the influence of the three supplementary cementitious materials on concrete's compressive strength. The research concerning the influence of two or more kinds of supplementary cementitious materials on concrete's compressive strength is still unclear. Moreover, there is a lack of clarity on the optimum proportion of one or more certain cementitious materials in practical engineering or experiments. To overcome these problems, this study adopts the concrete compressive strength development over time (CCSDOT) model, which generates an explicit formula to conduct quantitative research based on extensive data. The CCSDOT model performs well in fitting the compressive strength development of concrete containing cement, slag, fly ash, and limestone flour. The results reveal the nature of the influence of the three supplementary cementitious materials on concrete's compressive strength through the parameter analysis in the model. Two application cases are analyzed concerning the selection of the three supplementary cementitious materials and design of concrete mix proportion for practical engineering. It is concluded that the CCSDOT model and the method in this study can possibly provide guidance on both the selection of supplementary cementitious materials and the design of optimal concrete mix proportion for practical engineering. Therefore, the study is highly essential and useful.

Keywords: compressive strength; supplementary cementitious material; CCSDOT model; influence; optimal mix proportion

1. Introduction

In recent years, urbanization and the rapid development of large-scale infrastructure have created a huge demand for concrete and Portland cement [1]. Considering environmental protection, energy conservation, and resource benefits [2], more and more supplementary cementitious materials, including slag [3], fly ash [4], and limestone flour [5], are added into concrete as partial cement replacement material. In addition, the three supplementary cementitious materials have significant influence on the compressive strength of concrete [6]. Compressive strength is assumed to be one of the most important and essential properties of concrete, since it usually shows the overall quality of concrete [7]. Moreover, slag, fly ash, and limestone flour can enhance the durability [8–12], workability [10,12,13], and permeability [10,14] of concrete.

Slag has been successfully utilized in many countries around the world, achieving technical benefits in the construction industries in recent years [3,15]. Meanwhile, fly ash has also been used as a partial replacement of cement in concrete because of its pozzolanic effect [4]. However, fresh concrete incorporated with fly ash and cement reacts more slowly than that incorporated with cement only at an early age, especially at a high-volume replacement, because of fly ash's lower hydration rate [16,17]. Therefore, the maximum compressive strength of concrete incorporated with fly ash needs more time to gain [4]. Adding limestone flour into concrete as a partial cement replacement has been a research hotspot over the past two decades. One of the most common utilizations for limestone flour, cited in the open literature, is as a mineral admixture to improve workability of concrete [5,18,19]. Moreover, limestone flour works well in reducing the expansion associated with sulfate attacks [20] and decreases the cumulative amount of heat produced during hydration [21].

Numerous studies illustrate how the utilization of slag, fly ash, and limestone flour can improve the workability of fresh concrete and the durability of hardened concrete [6,8,22–25] due to their pozzolanic reaction and micro-aggregate effect. Some studies have even reported that the use of slag, fly ash, and limestone flour can reduce the heat of hydration and thermal cracking of concrete [26–28]. Oner [8] indicates that the use of slag can reduce the porosity of concrete and improve the compressive strength of concrete. A laboratory investigation on the optimum level of slag for the compressive strength of concrete is presented, and the results show that the compressive strength of concrete increases as the slag content increases, up to an optimal point, over which the compressive strength decreases because of the nature of slag. The optimum level of slag content for maximizing the compressive strength is around 55%–59% of the total binder content by weight.

Many researchers have also studied the influence of fly ash on the compressive strength of concrete. Wongkeo W. [29] has investigated the influence of high-calcium fly ash as a binary blended cement on compressive strength of self-compacting concrete, and the results indicate that binary blended cement with a high level of fly ash generally reduces the compressive strength of self-compacting concrete at all test ages (3, 7, 28, and 90 days). Lam M. N. T. [30] has revealed that the use of fly ash as cement substitution can improve the compressive strength of slag-roller compacted concrete pavement at long-term age. Moreover, Shaikh F. U. A. [31] has demonstrated the effect of ultrafine fly ash on compressive strength and durability properties of concrete containing high volume class F fly ash as partial replacement of cement. Some models have been developed to study the influence of fly ash on concrete's compressive strength. Wang X. Y. [32] presented a numerical procedure to evaluate the compressive strength development of high-volume fly ash concrete, which is valid for concrete with different water-to-binder ratios and different fly ash contents. Sarıdemir M [33] used a genetic programming model to study the effect of specimen size and shape on compressive strength of concrete containing fly ash.

Limestone flour is usually assumed to be an inert filler [21] and used as a partial replacement of cement in concrete [34–36], which mainly provides a filling effect and micro-aggregate effect in the concrete [37]. The fact that limestone flour does not participate in the chemical reaction is confirmed from both thermal analysis and backscattering scanning electron image analysis [35]. Besides, other studies also find that limestone flour has low reactivity [38,39]. Although limestone flour is deemed to be an inert material, it can still improve the very early-age compressive strength of concrete, workability, and stability of fresh concrete due to its micro-aggregate effect [40,41]. However, a few researchers have reported that limestone flour has been successfully used in conjunction with cement as an accelerator [42,43]. Vance et al. [1] illustrate the influence of limestone flour's particle size on hydration and mechanical properties of cement pastes. In a word, the influence of limestone flour on concrete compressive strength is still unclear.

There are numerous studies about the influence of each supplementary cementitious material on the compressive strength of concrete, such as slag [8], fly ash [24], and limestone flour [41]. Some studies demonstrate the influence of two or more kinds of supplementary cementitious materials on the concrete compressive strength [1,4,44]. However, most of these studies are specific to a certain engineering or a certain experiment [1,4,8,24], which cannot reveal the nature of the influence of supplementary cementitious materials on the concrete compressive strength. Moreover, the research about the influence of two or more kinds of supplementary cementitious materials on concrete compressive strength is still unclear. Furthermore, there is a lack of clarity on the optimum proportion of one or more certain cementitious materials in a practical engineering or experiment. In order to identify the nature of the influence of supplementary cementitious materials on concrete compressive strength, it is necessary to conduct comprehensive and quantitative research, which would require a lot of experimental and engineering data instead of just using certain engineering or experimental data.

To solve these problems, it requires a model with explicit expression and ability to adapt new data, which can fit and predict concrete compressive strength. There are two main types of models, conventional models and artificial intelligence models [45,46], to predict the compressive strength of concrete mixed with supplementary cementitious materials. Generally, conventional models are developed with a fixed equation with a limited amount of data and parameters [47]. If new data is different from the original data, then it is necessary to update not only the coefficients in the model but also the form of its equation. On the other hand, artificial intelligence models require a large training data set due to their "black-box" techniques [48], and always having no explicit expression. Both aforementioned models are flawed. The concrete compressive strength development over time (CCSDOT) model [49] generates explicit formulas that provide important advantages to reveal the nature of influence of the supplementary cementitious materials on concrete compressive strength. Therefore, it is adopted in this study. The inbuilt optimization algorithms make the CCSDOT model more adaptable to new data than conventional models.

This study employs 239 groups of mix proportions from 18 practical engineering experiments and lab reports to explore the nature of the proposed three supplementary cementitious materials. The application in engineering is presented as well. The investigation is expected to provide guidance on both the selection of supplementary cementitious materials and the design of concrete mix proportion for practical engineering; therefore, the study is highly critical. The overview of this study is shown in Figure 1.

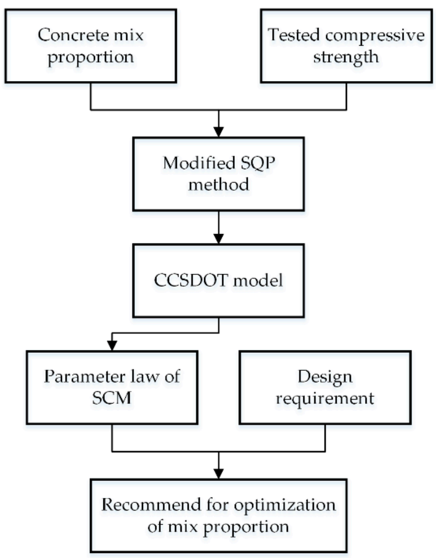

Figure 1. Overview of this study. CCSDOT: concrete compressive strength development over time; SQP: sequence quadratic programming; SCM: supplementary cementitious material.

2. Materials and Methods

2.1. Materials

There were 239 groups of concrete mix proportions (139 groups of concrete containing fly ash, 12 groups of concrete mixed with fly ash and limestone flour, 85 groups incorporated with fly ash and slag, 3 groups of concrete incorporated with limestone flour) from 18 practical engineering and lab reports adopted in this study. These reports were collected from the Guangzhao hydropower station, Guanyinyan hydropower station, Suofengying hydropower station, the Fengman hydropower station reconstruction project and others. These have been famous hydraulic engineering in China over the past few decades. The 18 practical engineering and lab reports include two-graded aggregate roller compacted concrete and three-graded aggregate roller compacted concrete. In addition to this, there are two\three\four-graded aggregate ordinary concrete. The diversity of concrete and its mix proportion are helpful to explore the nature of the influence of slag, fly ash, and limestone flour on the concrete's compressive strength. It is also able to demonstrate the applicability of the CCSDOT model. The details of data sources are listed in Table 1.

Table 1. Summary of the source of concrete mix proportions and compressive strength.

Kinds of Admixture	Construction Number	The Amount of Groups in Mix Proportions					
		RCC2	RCC3	OC2	OC3	OC4	CM
Fly ash	a	6	8			16	
	b	1	3	6			
	c	3	3		4	3	1
	d	1	1				
	e	2	4	8	8		
	f	2	3	4	1		
	g	2	3		4		
	h	2		4	4		
	i	2	1				
	j	4	4		5		
	k		3	8			
	l		1				
	m			1	1		
	n		1				
	o						1
Fly ash and limestone flour	a		3				2
	n		1				
	p					4	
	q		1				1
Fly ash and slag	r	2	11				
	a		6			15	26
	b		2	7	8		
	q	1		5			2
Limestone flour	n		3				

Table caption: a: Guanyinyan hydropower station; b: Suofengying hydropower station; c: Saige hydropower station; d: Guangzhao hydropower station; e: Fengman hydropower station reconstruction project; f: Shuangfengsi hydropower station; g: Shankouyan hydropower station; h: Ahai hydropower station; i: the stage III cofferdam of three gorges project; j: Kalasuke hydropower station; k: Kala hydropower station; l: Shatuo hydropower station; m: Jinggangshan hydropower station; n: A report named "Application of limestone flour and fly ash admixture in roller compacted concrete in cold area"; o: A report named "Application of natural volcanic ash as admixture in hydraulic concrete"; p: A report named "Effects of activity and content fluctuation of marble sand powder on concrete performance"; q: The fifth international conference on roller compacted concrete dams; r: Guandi hydropower station. Kinds of concrete, RCC2: two-graded roller compacted concrete; RCC3: three-graded roller compacted concrete; OC2: two-graded ordinary concrete; OC3: three-graded ordinary concrete; OC4: four-graded ordinary concrete; CM: cement mortar.

The basic information of the adopted two applications in practical engineering are briefed herein. The Fengman hydropower station reconstruction project is the largest dam in northeast China. The mix proportion of three-graded roller compacted concrete in Fengman is listed in Table 2. The water–binder ratio is 0.5; and the dosage of fly ash varies from 45% total cementitious material to 65% total cementitious material by weight. Accordingly, the compressive strength of three-graded roller compacted concrete is shown in Table 3.

Table 2. Mix proportions of three-graded roller compacted concrete.

Group	Constitution (kg/m^3)					VC (s)
	Water	Cement	Fly Ash	Sand	Aggregate	
1	86	94.6	77.4	658	1465	3.9
2	86	77.4	94.6	655	1460	3.0
3	86	60.2	111.8	653	1455	3.2

Table caption: VC: an index to measure the concrete consistence in Chinese Code (DL/T 5433-2009).

Table 3. Compressive strength of three-graded roller compacted concrete.

Group	Compressive Strength (MPa)		
	7 days	28 days	90 days
1	/	22.4	36.7
2	9.7	21.2	35.1
3	/	17.4	29.5

Slag is very abundant in southwest China, and a large amount of slag is piled up in the open air resulting in environmental pollution. Therefore, it is necessary to study the concrete in Suofengying, which mixed with slag. The mix proportions of three-graded roller compacted concrete in Suofengying is shown in Table 4. The water–binder ratio is 0.55 and the dosage of supplementary cementitious material (slag and fly ash) varies from 20% of the total cementitious material to 60% of the total cementitious material by weight. Accordingly, the compressive strength of three-graded roller compacted concrete in Suofengying is shown in Table 5.

Table 4. Mix proportions of the Suofengying three-graded roller compacted concrete.

Group	Constitution (kg/m^3)					
	Water	Cement	Fly Ash	Slag	Sand	Aggregate
1	75	109	27	0	801	1488
2	75	109	14	14	802	1489
3	81	118	0	29	818	1454
4	75	96	41	0	800	1485
5	75	82	55	0	797	1481
6	75	82	27	27	798	1482
7	75	68	68	0	794	1477
8	75	55	82	0	791	1473

Table 5. Compressive strength of the Suofengying three-graded roller compacted concrete.

Group	Compressive Strength (MPa)				
	7 days	28 days	90 days	180 days	360 days
1	18.5	32	43.2	45.2	46.5
2	24.1	31.7	43.2	46.0	47.2
3	22.5	32.7	44.5	46.7	47.9
4	17.9	29	40.6	42.8	44.4
5	15.6	26.4	37.2	39.5	43.4
6	16.1	27.2	38.3	40.0	44.2
7	11.2	22	31	38.8	42.6
8	9.6	16.9	27.8	33.3	37.0

2.2. Methods

2.2.1. Concrete Compressive Strength Development Over Time Model

The explicit formulation of CCSDOT model is expressed in Equation (1) below:

$$\begin{aligned} S_t &= S_C\left(q_C^{i_C} + ss_{SL}q_{SL}^{i_{SL}} + ss_{FA}q_{FA}^{i_{FA}} + ss_{LF}q_{LF}^{i_{LF}}\right) \\ &\times\left[1 + \left(\lambda_C q_C^{i_C} + \lambda_{SL}q_{SL}^{i_{SL}} + \lambda_{FA}q_{FA}^{i_{FA}} + \lambda_{LF}q_{LF}^{i_{LF}}\right)ln\frac{t}{28}\right] \end{aligned} \quad (1)$$

where S_t is the concrete compressive strength after t days; S_C is the 28-day compressive strength of concrete mixed with cement; q_C, q_{SL}, q_{FA}, and q_{LF} are the percentages of each cementitious material's content by weight; i_C, i_{SL}, i_{FA} and i_{LF} denote the impact index of cement, slag, fly ash, and limestone flour, respectively; ss_{SL}, ss_{FA} and ss_{LF} are the 28-day compressive strength contribution coefficient of slag, fly ash, and limestone flour; λ_C, λ_{SL}, λ_{FA} and λ_{LF} indicate the factor of the compressive strength in the later period (more than 28 days) of cement, slag, fly ash, and limestone flour respectively.

Besides the CCSDOT model, this study also adopts the modified sequence quadratic method, with the monitoring technology combining constraint condition and objective function, and temporary expansion of the feasible domain method, to obtain the optimum solution of Equation (1). Interested readers can refer to Liu [49]. Liu only applied the CCSDOT model to the green concrete. In this study, the CCSDOT model is applied in 18 practical engineering and lab reports, covering roller compacted concrete, ordinary concrete, etc. In brief, the overview of the model and methodology is shown in Figure 2 [49].

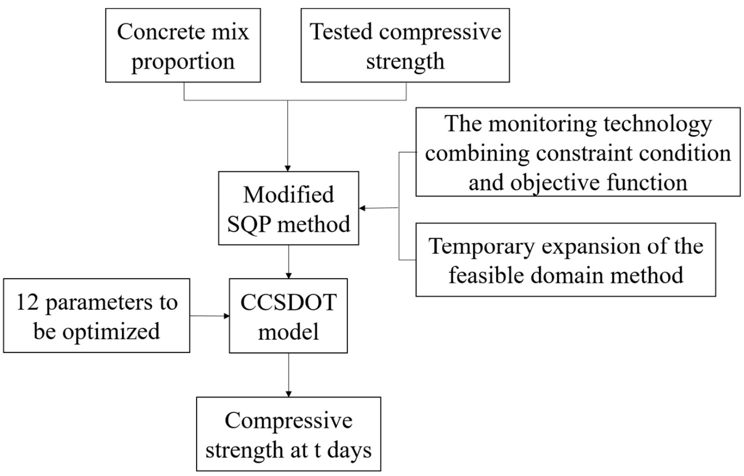

Figure 2. Overview of the model and methodology. SQP: sequence quadratic programming; CCSDOT: concrete compressive strength development over time.

2.2.2. Experimental Setup

In order to find the nature of the influence of the three supplementary cementitious materials on concrete compressive strength, a sophisticated experimental setup was proposed in this study. The detailed procedures are described as follows.

First, according to the composition of supplementary cementitious materials in concrete, 239 groups of concrete mix proportions were divided into 4 categories. Concrete in category (a) was mixed with fly ash only. Concrete in category (b) was mixed with fly ash and limestone flour. Concrete in category (c) was mixed with fly ash and slag, while concrete in category (d) was mixed with limestone flour only. Each single group of concrete mix proportion contained, at least, two similar concrete mix proportions.

Next, we adopted modified sequence quadratic programming (SQP) [49], which combined the monitoring technology combining constraint condition and objective function and temporary expansion of the feasible domain method, and then put the data of concrete proportions and the corresponding tested compressive strength at each concrete age into the model. Afterwards, the 12 parameters, including S_C, ss_{SL}, ss_{FA}, ss_{LF}, i_C, i_{SL}, i_{FA}, i_{LF}, λ_C, λ_{SL}, λ_{FA}, λ_{LF}, could be calculated. Using the calibrated 12 parameters and the given concrete proportions, we got the fitted compressive strength of concrete at each age of concrete. By comparing the fitted value with the tested concrete compressive strength, the error was obtained. Root mean squared relative error and the mean root mean squared relative error were utilized in this study to measure the error level. All of the calculated parameters were classified and analyzed to reveal the nature of the influence of slag, fly ash, and limestone flour on concrete compressive strength.

Finally, two applications in practical engineering were carried out. This study adopted the mix proportion and compressive strength data of three-graded roller compacted concrete from the Fengman hydropower station reconstruction project to establish the relationship among the compressive strength, concrete age, and dosage of fly ash. The concrete age range was from 7 to 180 days with a minimum interval of 1 day. The fly ash content ranged from 0% to 80% with a minimum interval of 1% by weight. The mix proportion and compressive strength data of three-graded roller compacted concrete, which mixed with fly ash and slag from the Suofengying hydropower station, were also used in this study. The content of supplementary cementitious material, which contained slag and fly ash, ranged from 20% to 60% with a minimum interval of 10% by weight, while the minimum interval of slag usage was 1% in each case. The curing time was from 1 to 180 days, with a minimum interval of 1 day.

2.2.3. Performance Measurement and Abbreviation

Two performance-measurement equations are used to explore the accuracy of the fitted value of CCSDOT model.

Root mean squared relative error [50] (*RMSRE*):

$$RMSRE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\frac{P_i - T_i}{T_i})^2} \quad (2)$$

where P_i is the fitted value; T_i is the tested value; n is the volume of data in a group of proportions. Each group of proportions contains two groups at least.

MRMSRE is the mean value of *RMSRE*:

$$MRMSRE = \frac{1}{m}\sum_{j=1}^{m} RMSRE_j \quad (3)$$

where $RMSRE_j$ is the root mean squared relative error of the j^{th} group of proportions; m is the volume of the proportion groups. In addition, the abbreviations in the rest of this study are listed in Table 6.

Table 6. Abbreviation in the rest of this study.

Abbreviation	Implication
SL	Slag
FA	Fly ash
LF	Limestone flour
C	Cement
FA + *SL*	Fly ash and slag
FA + *LF*	Fly ash and limestone flour
$ss_{FA}\ (FA + SL)$	the 28-day compressive strength contribution coefficient of fly ash in the concrete mixed with fly ash and slag
$ss_{FA}\ (FA)$	the 28-day compressive strength contribution coefficient of fly ash in the concrete mixed with fly ash
$ss_{FA}\ (FA + LF)$	the 28-day compressive strength contribution coefficient of fly ash in the concrete mixed with fly ash and limestone flour
$\lambda_{FA}\ (FA + SL)$	the factor in later periods of fly ash in concrete mixed with fly ash and slag
$\lambda_{FA}\ (FA)$	the factor in later periods of fly ash in concrete mixed with fly ash
$\lambda_{FA}\ (FA + LF)$	the factor in later periods of fly ash in concrete mixed with fly ash and limestone flour

3. Results

3.1. Performance of the CCSDOT Model

The 239 groups of concrete mix proportions are adopted in this study. Based on the modified SQP method, we substitute the proportions and the tested concrete compressive strength into the CCSDOT model, and obtain the fitted value. An intuitive comparison between the fitted value and the tested value of concrete compressive strength is shown in Figure 3, including concrete incorporated with fly ash (*FA*), concrete mixed with fly ash and limestone flour (*FA* + *LF*), concrete incorporated with fly ash and slag (*FA* + *SL*) and concrete mixed with limestone flour (*LF*). It is demonstrated that the fitted value is very close to the tested value graphically. The correlation coefficient (R^2) for 7-day, 28-day, 90-day, and 180-day compressive strength of concrete incorporated with a different kind of supplementary cementitious materials are listed in Table 7. Most of the R^2 are greater than 0.98.

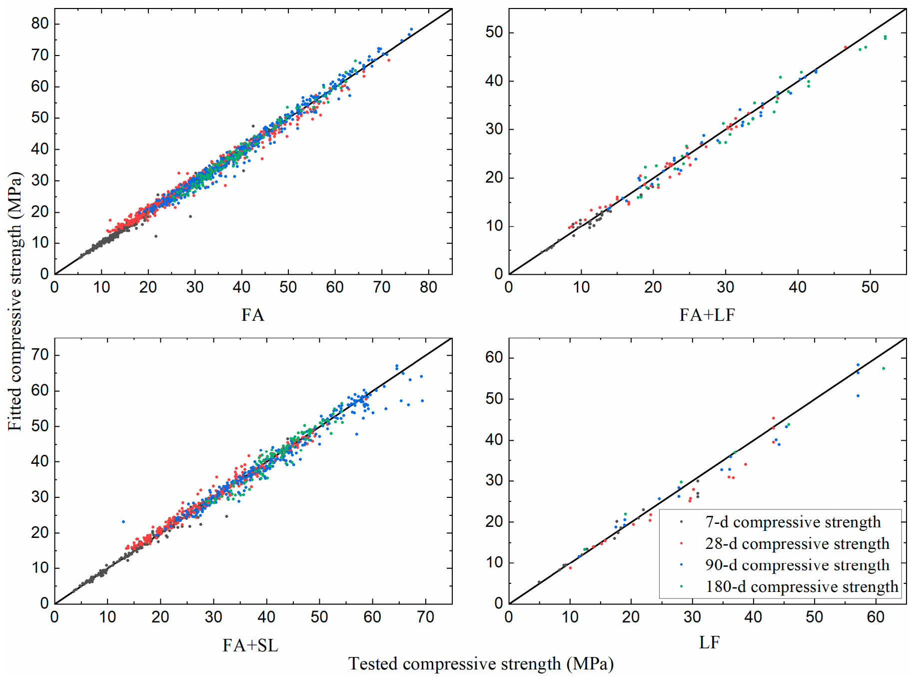

Figure 3. Relationship between tested compressive strength and fitted concrete compressive strength.

Table 7. Correlation coefficient (R^2) for 7-day, 28-day, 90-day, and 180-day compressive strength of concrete incorporated with different kind of supplementary cementitious materials.

Concrete Age	*FA*	*FA + LF*	*FA + SL*	*LF*
7-day	0.9946	0.9793	0.9946	0.9825
28-day	0.9928	0.9873	0.9906	0.9802
90-day	0.9928	0.9902	0.9802	0.9891
180-day	0.9914	0.9837	0.9670	0.9980

Moreover, we use $RMSRE_j$ to evaluate the error between the fitted and tested compressive strength of concrete as presented in Figure 4. The results are analyzed in four different scenarios, including concrete with fly ash, with fly ash and limestone flour, with fly ash and slag, and with limestone flour. *RMSRE* is generally small and confined between 0 and 10%. The *RMSRE* of concrete mixed with fly ash, and the *RMSRE* of concrete incorporated with fly ash and slag, are relatively small due to the sufficient data. In addition, the 25th percentile, median and 75th percentile of *RMSRE* of the four kinds of concrete are shown in Table 8. The *MRMSRE* for four scenarios are 3.9374%, 5.4667%. 4.0506%, and 7.4667% respectively. The *MRMSRE* of concrete with fly ash and that with fly ash and slag are acceptable in practical engineering, which requires no more than 5%. Since the quantity of concrete mix proportions are insufficient, the *MRMSRE* of concrete with fly ash and limestone flour and that with limestone flour only are slightly great. Considering each group of concrete mix proportion contain two or more similar mix proportions, the *MRMSRE* are still acceptable. In conclusion, the proposed model could fit the compressive strength of all four kinds of concrete fairly well, and can be used to deduce generic law of the influence of slag, fly ash, and limestone flour on concrete compressive strength.

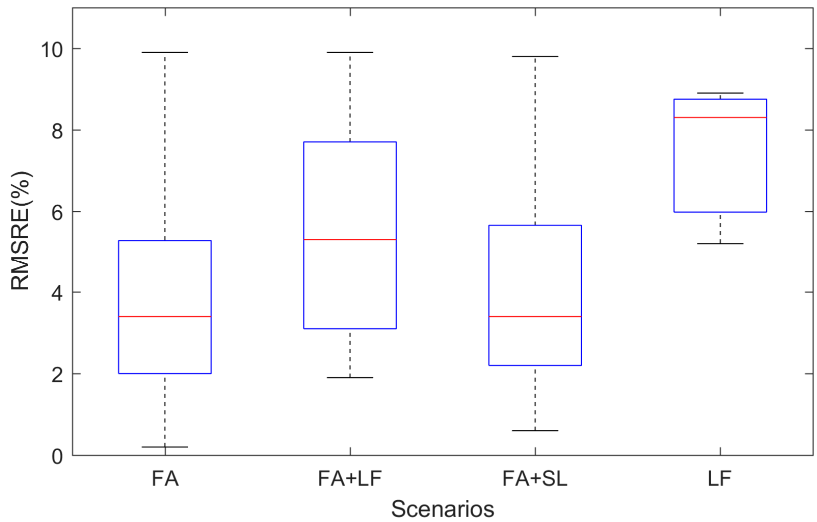

Figure 4. The root mean squared relative error of each kind of concrete. *FA*: concrete with fly ash; *FA + LF*: concrete with fly ash and limestone flour; *FA + SL*: concrete with fly ash and slag, and *LF*: concrete with limestone.

Table 8. The 25th percentile, median, and 75th percentile of root mean squared relative error of each kind of concrete.

	***FA* (a)**	***FA + LF* (b)**	***FA + SL* (c)**	***LF* (d)**
25th percentile	2.0%	3.1%	2.2%	6.0%
median	3.4%	5.3%	3.4%	8.3%
75th percentile	5.3%	7.7%	5.6%	8.8%

3.2. The Parameter Analysis for Each Cementitious Material in CCSDOT Model

3.2.1. Fly Ash

ss_{FA}, λ_{FA} and i_{FA} are present in Figures 5–7, respectively. Most of ss_{FA} are between −0.568 and −0.327 while the median of ss_{FA} is −0.415. ss_{FA} are almost smaller than 0 graphically, except four outliers. Those outliers are supposed to have a great relationship with the categories of fly ash. There are two general classes of fly ash, including low-calcium fly ash (ASTM Class F) produced by burning anthracite or bituminous coal and high-calcium fly ash (ASTM Class C) produced by burning lignite or sub-bituminous coal [44]. In the four outliers where the value of ss_{FA} is greater than 0 in Figure 5, the engineering or experiment adopts class C fly ash instead of class F fly ash. Since the reactivity of high calcium fly ash (class C) is much higher than class F fly ash [6] and class C fly ash exhibits similar properties to slag, therefor, the value of ss_{FA} is greater than 0. The detailed interpretation will be provided later in discussion. Most of λ_{FA} are between 0.376 and 0.638 while the median of λ_{FA} is 0.504. Graphically, most of i_{FA} are between 1.310 and 1.635 while the median of i_{FA} is 1.502 in Figure 7.

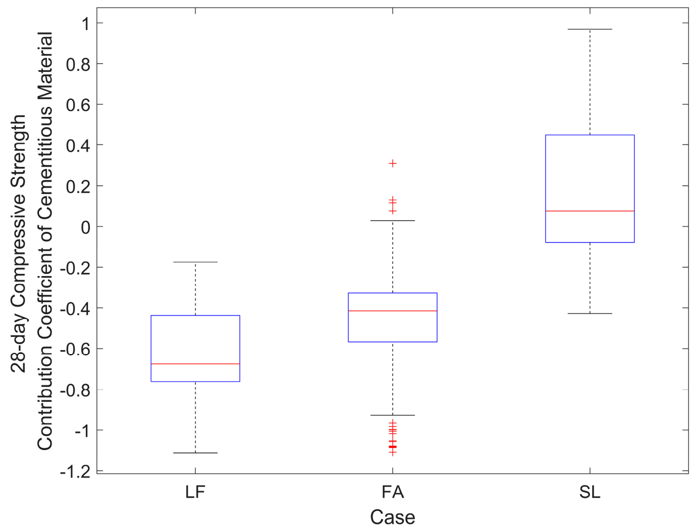

Figure 5. The 28-day compressive strength contribution coefficient of each cementitious material.

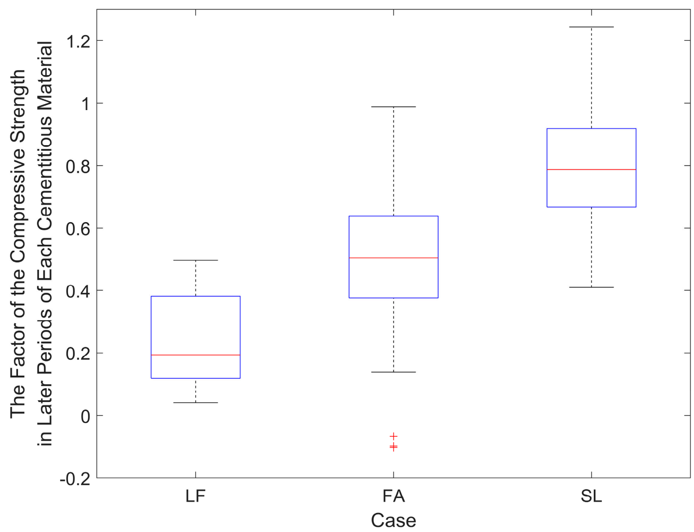

Figure 6. The factor of the compressive strength in later periods of each cementitious material.

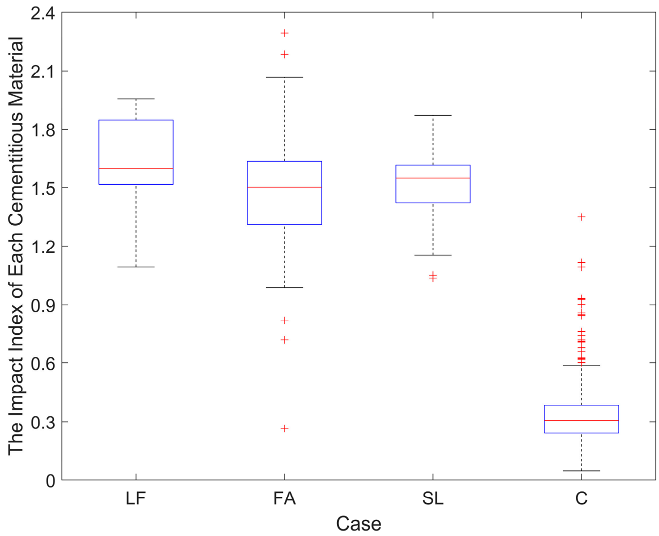

Figure 7. The impact index of four kinds of each cementitious material.

In addition, Figure 8a shows the relationship between the ss_{FA} and different kinds of concrete mixed with fly ash, including concrete incorporated with fly ash and slag, concrete incorporated with fly ash only, and concrete mixed with fly ash and limestone flour. In general, the $ss_{FA}(FA + SL)$ are smaller than the $ss_{FA}(FA)$, while the $ss_{FA}(FA)$ are smaller than the $ss_{FA}(FA + LF)$ on the whole. In order to further reflect the distribution of ss_{FA}, the 25th percentile, median, and 75th percentile of the ss_{FA} in different kinds of concrete are enumerated in Table 9. It's easy to conclude that the 25th percentile, median, and 75th percentile of $ss_{FA}(FA + SL)$ are smaller than those of $ss_{FA}(FA)$, while those of $ss_{FA}(FA)$ are smaller than those of $ss_{FA}(FA + LF)$ respectively.

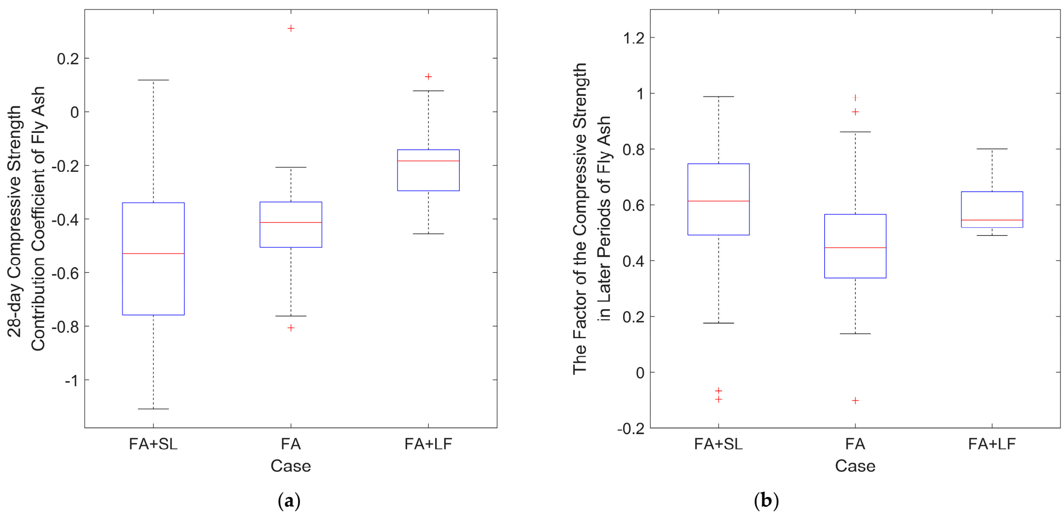

Figure 8. The 28-day compressive strength contribution coefficient of fly ash (**a**) and the factor of the compressive strength in later period of fly ash (**b**).

Table 9. The 25th percentile, median, and 75th percentile of 28-day compressive strength contribution coefficient of fly ash in different kinds of concrete.

	FA + SL	*FA*	*FA + LF*
25th percentile	−0.758	−0.507	−0.296
median	−0.529	−0.413	−0.184
75th percentile	−0.339	−0.336	−0.142

Figure 8b reveals the λ_{FA} in different kinds of concrete. Graphically, the λ_{FA} $(FA + SL)$ are greater than the λ_{FA} $(FA + LF)$ generally while the λ_{FA} $(FA + LF)$ are greater than the λ_{FA} (FA) on the whole. The compressive strength in later periods of concrete can be improved by adding fly ash into the concrete mixture, due to the pozzolanic activity and filling effect of fly ash. Moreover, the 25th percentile, median, and 75th percentile of λ_{FA} in different kinds of concrete are enumerated in Table 10.

Table 10. The 25th percentile, median, and 75th percentile of the factor in later periods of fly ash in different kinds of concrete.

	FA + SL	*FA*	*FA + LF*
25th percentile	0.491	0.338	0.518
median	0.613	0.445	0.545
75th percentile	0.747	0.565	0.646

3.2.2. Slag

ss_{SL}, λ_{SL} and i_{SL} are shown in Figures 5–7, respectively. Figure 5 shows most of ss_{SL} are between −0.078 and 0.449 while the median of the ss_{SL} is 0.078. Therefore, all of the ss_{SL} are smaller than ss_C which is equal to 1. In Figure 6, most of λ_{SL} are between 0.668 and 0.918, while the median of λ_{SL} is 0.788. In Figure 7, most of i_{SL} are between 1.423 and 1.616, while the median of i_{SL} is 1.551 visually.

3.2.3. Limestone Flour

ss_{LF}, λ_{LF} and i_{LF} are shown in Figures 5–7, respectively. In Figure 5, most of ss_{LF} are between −0.437 and −0.761 while the median of ss_{LF} is −0.676. Limestone flour is a kind of inert material [36]; therefore, there is almost no chemical action [34] to concrete. In early days, limestone flour even has a negative effect on concrete's compressive strength compared to cement. Therefore, the ss_{LF} are smaller than 0. In Figure 6, the λ_{LF} are between 0.118 and 0.381 generally; the median is 0.194. Limestone flour has a polygonal body with an irregular shape whilst its morphology is similar to cement. As a result, it can improve the gradation of fine powder when mixed into concrete. Through the micro-aggregate effect and filling effect of limestone flour, the mechanical bite force between the mortar and aggregate is increased. Thus, physical action of the limestone flour at later days exits. The λ_{LF} are greater than 0. In addition, most of i_{SL} are between 1.516 and 1.847, while the median of i_{SL} is 1.598.

3.3. Application in Practical Engineering

3.3.1. Application in Fengman Hydropower Station Reconstruction Project

Figure 9 shows the relationship between the concrete compressive strength and the concrete's age. The red, blue, and green curves indicate the dosage of fly ash in roller compacted concrete is 45%, 55%, and 65% of the total cementitious material by weight respectively. Based on Figure 9, it is easy to figure out the optimal concrete mix proportion to meet a certain design requirement. For example, if the design requirement is that the 28-day compressive strength of the roller compacted concrete should not be smaller than 25 MPa, the traditional experimental method will take much money, time and a lot of resources to get the precise maximum dosage of fly ash in the roller compacted concrete. However, by using the CCSDOT model and a few trial tests, it is easier and quicker to get the precise maximum dosage of fly ash in the roller compacted concrete. The maximum dosage of fly ash is 34% (the black line in the Figure 9), and the specific operation steps to obtain this value are as follows:

Step 1: put the proportions and the tested compressive strength of concrete from the trail tests into the CCSDOT model, then the 12 parameters can be calculated by using modified SQP. After parameters in the model are calibrated, the concrete compressive strength development over time model, which is suitable for this engineering, is obtained.

Step 2: keep the total amount of cementitious material unchanged, and make the fly ash content in concrete gradually increase from 0% to 80% by weight with 1% interval; then we get 81 concrete mix proportions.

Step 3: substitute the 81 mix proportions into the calibrated CCSDOT model, then we obtain 81 corresponding curve of concrete compressive strength development over time in Figure 9.

Step 4: according to the concrete age and compressive strength in the design requirements, maximum dosage of fly ash can be quickly obtained from Figure 9 by using the abscissa and ordinate.

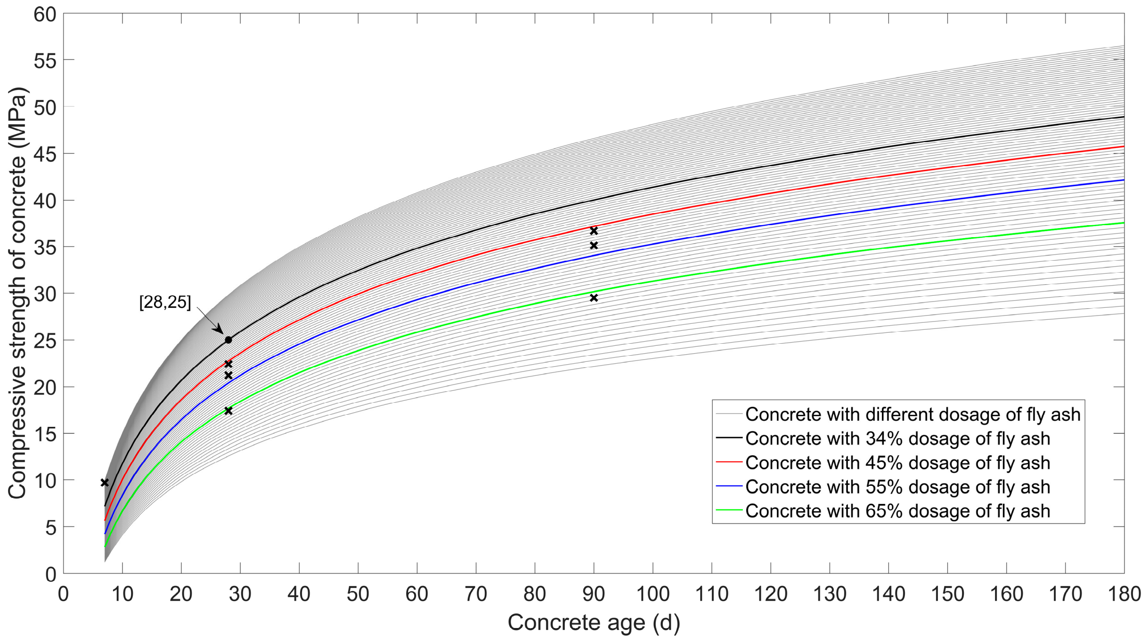

Figure 9. The relationship between the concrete's age and compressive strength with 1% interval of the fly ash's dosage. Black cross marks are tested value.

Figure 10 indicates the change characteristic of the compressive strength of concrete with the increase of fly ash content. The concrete compressive strength decreases as the fly ash dosage increases throughout all the concrete's age. The black, red, blue, and green curves denote the concrete at 7, 28, 90, and 180 days respectively. In order to better clarify the relationship among fly ash content, concrete compressive strength, and concrete's age, the relative compressive strength of the concrete is introduced to show the influence of fly ash content on the concrete's compressive strength at different ages. Figure 11 shows the relationship between the content of fly ash and the relative compressive strength of the concrete. Relative compressive strength of concrete at a certain age decreases as the increasing of fly ash content, and relative compressive strength of concrete with a certain content of fly ash deceases as the increasing of concrete's age. Table 11 shows the compressive strength of concrete with 0%, 40%, and 80% content of fly ash by weight at 7 days, 28 days, 90 days, and 180 days, respectively. As you can see, fly ash content has less influence on the concrete's compressive strength as the age increases.

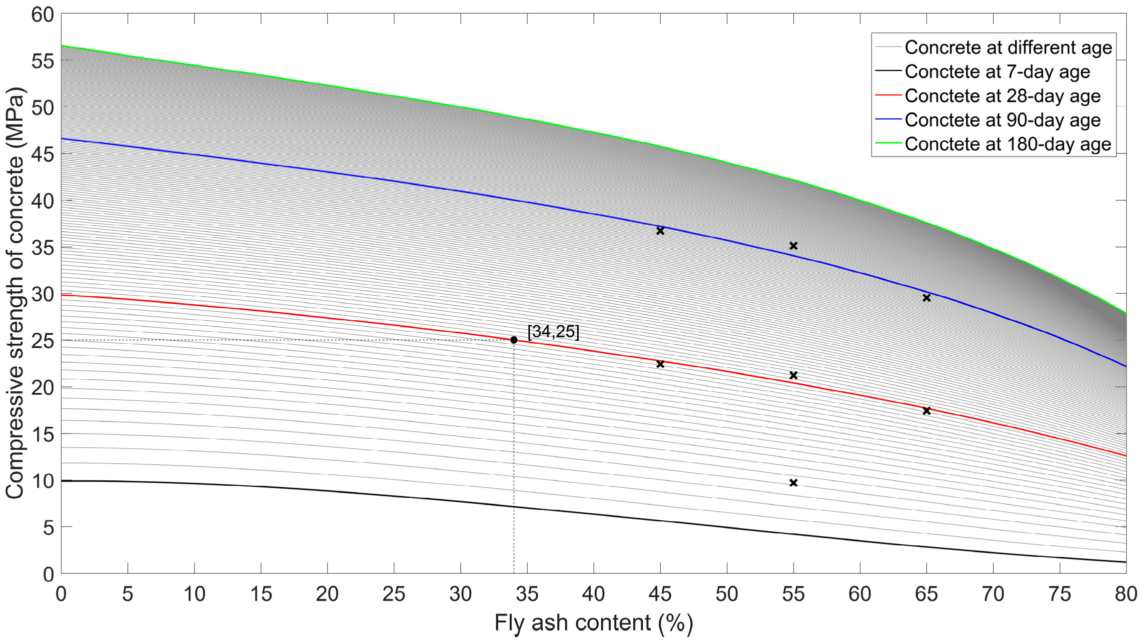

Figure 10. The relationship between fly ash content and compressive strength of concrete day-by-day. Black cross marks are tested value.

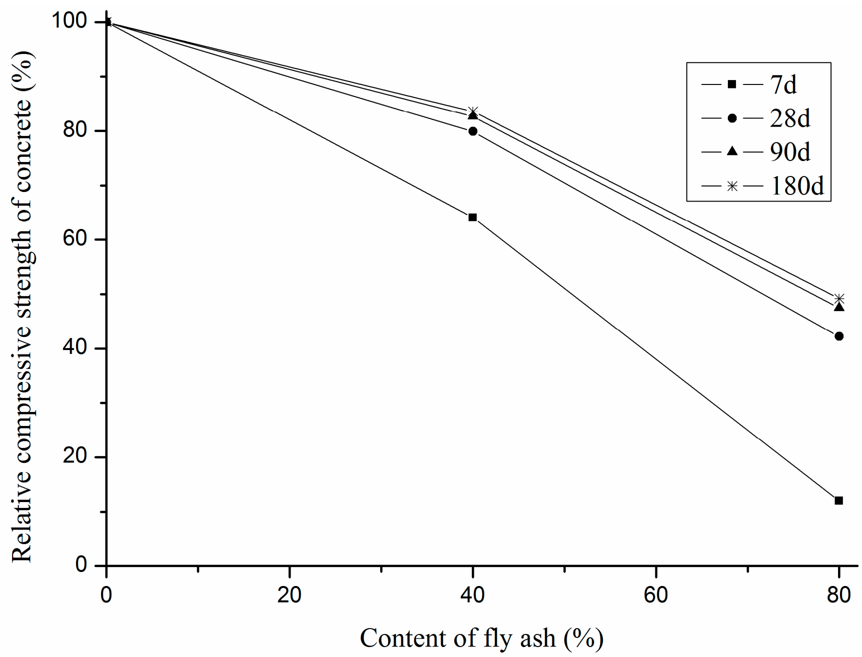

Figure 11. The relationship between the content of fly ash and the relative compressive strength of concrete.

Table 11. Compressive strength of concrete with 0%, 40%, and 80% content of fly ash.

Concrete Age (day)	Compressive Strength of Concrete (MPa)		
	0% Fly Ash	40% Fly Ash	80% Fly Ash
7	9.89	6.34	1.19
28	29.81	23.81	12.57
90	46.59	38.52	22.15
180	56.55	47.25	27.84

3.3.2. Application in the Suofengying Hydropower Station

Figure 12 shows the comparison of the concrete's compressive strength with different doses of supplementary cementitious materials (slag and fly ash) at different ages. The content of supplementary cementitious materials varies from 20% to 60% by weight. Figure 12a–e demonstrate the maximum dosage of supplementary cementitious materials is 20%, 30%, 40%, 50%, and 60% by weight respectively. The green, blue, red, and black thick curves indicate the concrete at 180, 90, 28, and 7 days respectively. As the maximum amount of supplementary cementitious materials increases, the compressive strength of concrete with a 0% content of slag decreases; therefore, the compressive strength decreases while the amount of fly ash increases. Relatively, as the amount of supplementary cementitious materials increases, the 180-day compressive strength of concrete with a 0% content of fly ash increases. Therefore, slag is beneficial to the compressive strength of concrete in later periods.

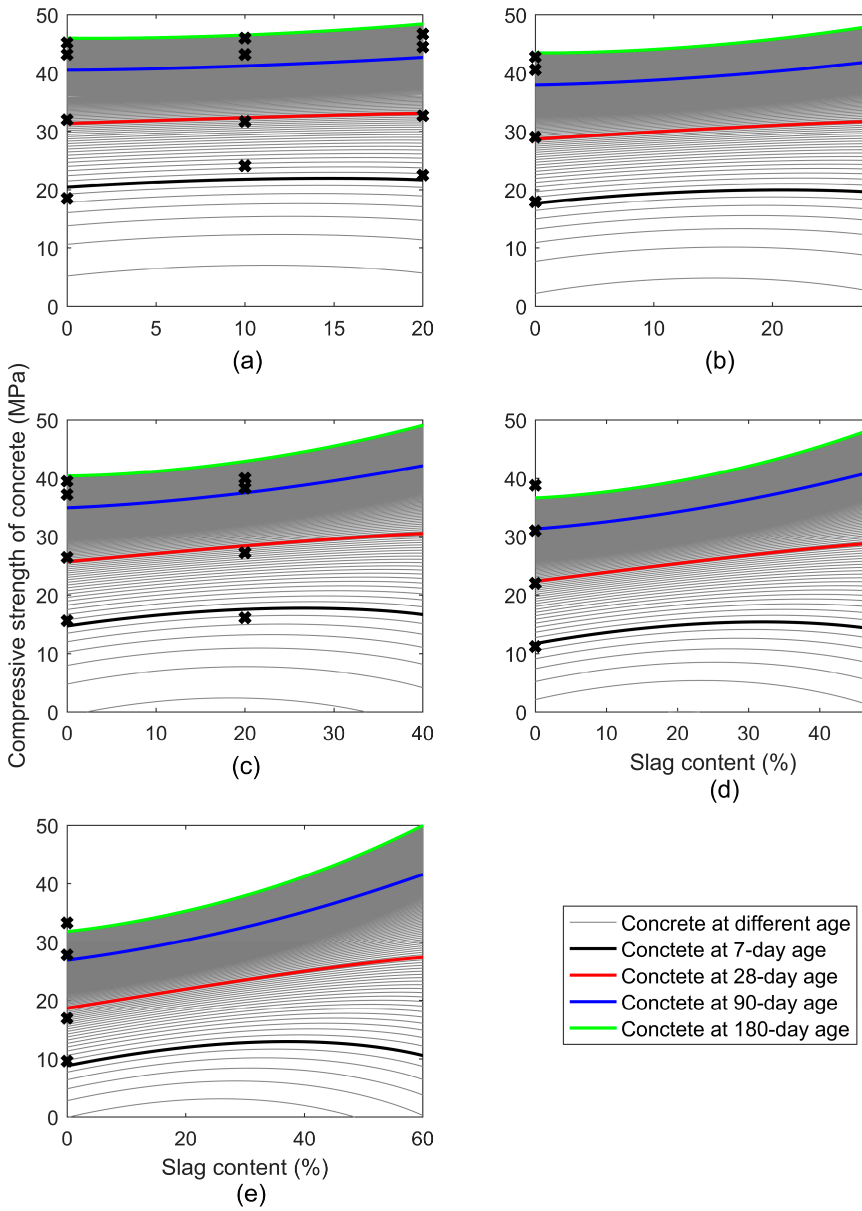

Figure 12. Comparison of concrete compressive strength with different does of supplementary cementitious materials (slag and fly ash) at different ages day by day. The content of supplementary cementitious materials is 20% in (**a**), 30% in (**b**), 40% in (**c**), 50% in (**d**) and 60% in (**e**). Black cross marks are tested value.

For each single figure, the compressive strength of concrete at a 28-day age, 90-day age, and 180-day age increases as the content of slag increases, visually. Moreover, the compressive strength increases as the curing time goes on, which is conformed to the objective pattern. We could select the optimal concrete mix proportion to meet a certain demand through the proposed CCSDOT model and these figures. The compressive strength of concrete at a certain age could also be predicted with the given concrete mix proportion easily.

4. Discussion

4.1. Speculative Hypothesis

4.1.1. Fly Ash

The hydration product of fly ash is similar to calcium silicate hydrate (C-S-H), which is the hydration product of the silicate cement. However, the reaction would not begin until several days after the concrete has been mixed. If there is class F fly ash, the reaction may take a week, or even longer to occur. Moreover, the glass phase in the fly ash dissolves only after the PH value of the liquid phase pore water reaches 13.2. The silicate cement in the mixture must be hydrated to a certain extent, in order to increase the alkalinity of the liquid phase pore water. As a result, most of the ss_{FA} are smaller than 0 in Figure 5. Consistent with the research results by Rong et al. [16], the early age compressive strength development may be delayed by using fly ash as cement replacement. Dadsetan et al. [4] also indicate that the concrete mixed with fly ash reacts more slowly than conventional concretes made with Portland cement. Therefore, the maximum strength needs more time to gain.

Slag is more active than fly ash at early days. The presence of slag inhibits the pozzolanic reaction of fly ash in the early days. Only when the PH value of the pore water is high enough (about 13.2), the fly ash hydration products will accumulate on and near the surface of the fly ash particles. Therefore, the hydration products of fly ash still exist in the form of original spherical particles at early days when mixed with slag. In conclusion, the hydration reaction of fly ash requires high alkalinity of pore water. However, when it is mixed with slag, the basicity of pore water decreases due to the hydration reaction of slag. As a result, the reactivity of fly ash decreases in such mixtures and most of ss_{FA} $(FA + SL)$ are smaller than the ss_{FA} (FA) in Figure 8a. Limestone flour plays a role of micro aggregate and highlights the importance of fly ash, making most of ss_{FA} $(FA + LF)$ greater than the ss_{FA} (FA) in Figure 8a.

As the hydration speed of fly ash is slower than slag, fly ash could play a more important role during later period compared to slag. The hydration products of fly ash are diffused and precipitated inside the capillary pores with time; thus, reducing the capillary porosity rate and refining the pore structure. Meanwhile, limestone flour plays the role of micro aggregate throughout the whole life of the concrete. Hence, most of λ_{FA} $(FA + SL)$ are greater than most of λ_{FA} $(FA + LF)$. At the meantime, fly ash is more active than limestone flour and, thus, there is almost no physical action at later days. Most of λ_{FA} $(FA + LF)$ are smaller than λ_{FA} $(FA + SL)$ while most of λ_{FA} $(FA + LF)$ are greater than λ_{FA} (FA) in Figure 8b.

4.1.2. Slag

When silicate cement and slag are mixed with water, silicate cement begins to hydrate first and release calcium ions and aluminum ions into the solution. Meanwhile, only a little slag reacts immediately. The slag reacts with calcium hydroxide released by silicate cement. Consequently, C-S-H is formed, and then it reacts with other basic hydroxides as time goes on. The initial hydration of slag is slow because it depends on the rate at which the hydroxide ions are dissolved in the hydrated silicate cement. Consequently, the early age strength of slag concretes is lower than the control concretes with the same binder content, and the ss_{SL} are smaller than ss_C, which is equal to 1.

However, as the curing period extends, the slag releases alkali gradually and the compressive strength increases gradually for the slag concretes, since the pozzolanic reaction emerges gradually and the formation of calcium hydroxide requires time. Thus, compressive strength of concrete with slag would show a long-term growth trend due to the reaction of slag sustaining for a long time. Moreover, Roy [51] quotes that after hydrating for 3 days, only 8%–16% slag is hydrated; about 30% to 37% slag would be hydrated after 28 days. In conclusion, λ_{SL} is extremely high and the median of λ_{SL} even reaches 0.788, which is highest among the three supplementary cementitious materials.

4.2. The Comparison among Fly Ash, Slag, and Limestone Flour

In Figure 5, the ss_{LF} are smaller than the ss_{FA} generally while the ss_{FA} are smaller than the ss_{SL} visually. It mainly depends on the activity of each cementitious material. Limestone flour is an inactive material; therefore, there is almost no chemical action to the concrete. In the early age of concrete, slag is more active than fly ash because of the higher pozzolanic reactivity [28]. Therefore, the results of a large number of engineering data or experiment data show that the 28-day compressive strength contribution coefficient of slag (ss_{SL}) are greater than ss_{FA}, while ss_{FA} are greater than ss_{LF}. Moreover, this conclusion is the same as the finding by Zhang et al. [21].

It is not difficult to observe the same characteristics in Figure 6: the λ_{LF} are smaller than the λ_{FA} generally, while the λ_{FA} are smaller than the λ_{SL} on the whole. Since limestone flour still only has a physical effect on the concrete at later days, the λ_{LF} are the minimum among the three parameters. Slag plays its full effect to concrete earlier than fly ash; however, fly ash generally needs a few years to complete its chemical reaction. Therefore, the λ_{FA} are smaller than the λ_{SL}.

The impact index of each cementitious material including cement is shown in Figure 7. Moreover, Table 12 reveals the 25th percentile, median, and 75th percentile of the impact index of each cementitious material. The i_C are much smaller than the other three parameters, i_{SL}, i_{FA}, and i_{LF}. This is because the 28-day compressive strength of concrete increases rapidly with increases in the cement content at first, and when the content of cement reaches a certain level, the 28-day compressive strength of concrete increases slowly with an increase in the amount of cement. In such cases, the impact index of cement is greater than 0 and smaller than 1. On the other hand, the 28-day compressive strength of concrete increased slowly with increases in the slag, or fly ash, or limestone flour content at first, and when the content of fly ash reaches a certain level, the 28-day compressive strength of concrete increases quickly. In this case, the impact index of slag, or fly ash, or limestone flour is always greater than 1. A more detailed explanation of this phenomenon can be found in Liu et al. [49].

Table 12. The 25th percentile, median, and 75th percentile of the impact index of each cementitious material.

	LF	*FA*	*SL*	*C*
25th percentile	1.516	1.310	1.423	0.241
median	1.598	1.502	1.551	0.307
75th percentile	1.847	1.635	1.616	0.384

4.3. Interpretation of Parameter Values with Biggish Dispersion Degree

There are three main reasons to explain the high dispersion of each mentioned fly ash coefficient. Firstly, there are many influences from other admixtures, such as slag and limestone flour. Secondly, fly ash is a collected industrial by-product of calcining coal powder in power stations; therefore, the quality of fly ash fluctuates greatly. Thus, the fluctuation in the quality of the fly ash is mainly reflected in the content of vitreous body, particle characteristics, particle size distribution, as well as the presence of M_gO and other substances. Consequently, there are periodic changes in the operation of the power station and differences in the fly ash produced by different power stations. Moreover, the coal used in the same power plant may not be homogeneous. Thirdly, fly ash contributes more to the concrete than it does to the mortar because of the physical action of fly ash in the concrete (except from the chemical action). The main physical action is that fly ash can be filled with coarse aggregate particles while there is no such physical effect in mortar mixed with fly ash.

Besides, there is a high dispersion of ss_{SL} in Figure 5. There are also three interpretations. Firstly, the fineness of cement in each engineering project and experiment varies; and the finer the cement is, the faster the activity excitation speed of slag is. Secondly, in the middle and later stage of hydration, the hydration activity of slag is related to its fineness. The finer the slag is, the more active the activity is. At last, the experiment environment and background vary greatly, such as curing condition and specimen size.

5. Conclusions

This study adopts the CCSDOT model with the modified SQP method and 239 groups of concrete mix proportions with tested compressive strength, accordingly, to find the nature of the influence of slag, fly ash, and limestone flour on concrete compressive strength. In addition, two application cases are analyzed for the selection of the three supplementary cementitious materials and the design of concrete mix proportion for practical engineering. The main findings of our study are as follows:

(1) The CCSDOT model has good performance in fitting the compressive strength of 239 groups of concrete from 18 practical engineering experiments and lab reports, and the *RMSRE* of each group is acceptable in practical engineering.

(2) Through the calculation of numerous data by the CCSDOT model, the main parameter laws of the CCSDOT model can be obtained as follows: most of the ss_{FA} are between −0.568 and −0.327, while the median of ss_{FA} is −0.415. The ss_{SL} are generally between −0.078 and 0.449, while the median of ss_{SL} is 0.078. Most of the ss_{LF} are between −0.437 and −0.761, the median of ss_{LF} is −0.676. Most of the λ_{SL} are between 0.668 and 0.918, while the median of λ_{SL} is 0.788. Most of the λ_{LF} are between 0.118 and 0.381 and the median is 0.194.

(3) The comparison among ss_{FA} from three kinds of concrete incorporated with fly ash is demonstrated in this study. Most of the ss_{FA} $(FA + SL)$ are smaller than the ss_{FA} (FA), while most of the ss_{FA} (FA) are smaller than the ss_{FA} $(FA + LF)$. Meanwhile, most of the λ_{FA} $(FA + SL)$ are greater than the λ_{FA} $(FA + LF)$, while most of the λ_{FA} $(FA + LF)$ are greater than the λ_{FA} (FA).

(4) The comparison among slag, fly ash, and limestone flour indicates that most of the ss_{LF} are smaller than the ss_{FA}, while most of the ss_{FA} are smaller than the ss_{SL}. In the meantime, most of the λ_{LF} are smaller than the λ_{FA}, while most of the λ_{FA} are smaller than the λ_{SL}.

(5) Application in the Fengman hydropower station reconstruction project demonstrates that the maximum content of fly ash in Fengman hydropower station reconstruction project can be quickly found by using the CCSDOT model. Meanwhile, the usage of slag and fly ash in the Suofengying hydropower station can also be quickly found through the CCSDOT model to meet the design and financial requirements. It is helpful to guide the design and optimization of the engineering mix proportions.

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