buildings

Article

Contribution of Steel Fiber to the Mechanical Property Improvement of C80 Concrete Produced with a High Amount of Artificial Sand Powder

Qingqing Xie [1,2,3,4], Dongxing Xuan [5], Bo Shen [1,3,*] and Kejian Ma [1,3]

1 Space Structures Research Center, Guizhou University, Guiyang 550025, China
2 College of Civil Engineering, Guizhou University, Guiyang 550025, China
3 Key Laboratory of Structure Engineering of Guizhou Province, Guizhou University, Guiyang 550025, China
4 Guizhou Provincial Key Laboratory of Rock and Soil Mechanics and Engineering Safety, Guizhou University, Guiyang 550025, China
5 Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China
* Correspondence: bshen@gzu.edu.cn

Abstract: Due to the high price of river sand, its shortage and unsustainable extraction from the environment, artificial sand (AS) has been promoted as a fine aggregate for producing concrete. However, it has been acknowledged that a high content of limestone powder (LP), up to 15 wt.%, as a by-product in AS coexists and it has an adverse impact on the mechanical properties of concrete. To compensate for the performance loss of C80 concrete with a high LP content to the applications of concrete on a large scale, this study evaluates the contribution of steel fiber content to the performance improvement of concrete by means of a developed statistical method. Experimental results show that when increasing the LP in concrete over 5%, it can influence axial compression, flexural intensity, splitting tension and the modulus of elasticity, in particular, presenting an obvious decrease in axial compressive intensity, splitting tension and modulus of elasticity. Incorporating steel fibers in such concrete prepared with a high amount of artificial sand powder is a way to compensate for its performance loss. Referring to the experimental results and probability theory, the probability density function of the characteristic value of mechanical characteristic of one type of concrete and the difference between the characteristic values of mechanical characteristics of any two concretes were developed to establish a scientific criterion that can be used to compare the sizes of any two characteristic probability values, which is superior to the comparative approach of arithmetic averages in publications. By adopting this method, the high-strength concrete with a high LP and steel fiber content could be applied in engineering practices from the point of view of its mechanical properties. Meanwhile, the study provides an evaluation method for other scientific research on the size comparison of any two stochastic physical variables.

Keywords: artificial-sand concrete; limestone powder; possibility density distribution; characteristic value of mechanical characteristic; steel fiber

Citation: Xie, Q.; Xuan, D.; Shen, B.; Ma, K. Contribution of Steel Fiber to the Mechanical Property Improvement of C80 Concrete Produced with a High Amount of Artificial Sand Powder. *Buildings* **2023**, *13*, 602. https://doi.org/10.3390/buildings13030602

Academic Editor: Jan Fořt

Received: 31 December 2022
Revised: 16 February 2023
Accepted: 18 February 2023
Published: 24 February 2023

1. Introduction

At present, due to the high price of river sand, its supply shortage and unsustainable sand-extraction processes from the environment, especially in the karstic feature areas of Guizhou province, China, artificial sand (AS) crushed from natural stone has been promoted as a replacement of river sand in concrete production [1]. In the production process of AS, its rock powder (RP) content can be generated up to 15% by mass [2]. For C30~C45 and C50~C55, the limit of the RP content in AS is specified to be 10% and 7%, respectively [3]. When the concrete strength grade is higher than C60, the contents of RP in AS should not exceed 5% [4]. Excessive content of RP in AS affects the mechanical characteristics of concrete, even its durability. Normally, washing is a method to reduce the RP content from AS, while it increases the production cost and causes water pollution. In order to prepare high-strength concrete (i.e., C80) on a large scale, other attempts are welcome and necessary to avoid the influence of a high amount of RP on the mechanical performance loss of high-strength concrete.

Choudhary et al. [5] reported that the use of 10% RP as cement substitutes can cause the concrete to attain the optimum mechanical performance. Li et al. [6] reported that replacing cement with the 5% RP had little effect on the strength of concrete; however, when the substitution of RP for cement exceeded 10%, the strength of concrete was reduced. Ma et al. [7] found that when the addition of RP to cement exceeded 10%, the compressive strength of concrete was considerably reduced. Hamdy et al. [8] found that, in cement, the addition of 5% of marble powder did not affect the cement's properties. RP instead of AS, up to 15% of the AS weight, can reduce the use of fine aggregates [9,10] and also reduce RP environmental contamination [11]. Generally, the processing technology used for the acquisition of RP from AS is complicated, generating a high cost owing to its coexistence with AS; therefore, the use of RP as a replacement of AS is convenient. Zhang et al. [12] and Xie et al. [13] reported that for concrete with a grade lower than C60, its compressive intensity decreased with a high content ($\geq$ 10%) of RP. Tang et al. [14], Febin et al. [10] and Shen et al. [15] reported that for concrete prepared with a C15~C55 grade, at a relatively low RP content ($\leq$ 6%), it may positively correlate with the compressive intensity. Generally, with an increase in RP, the strength and modulus of elasticity decreased [16,17]. Then, Wu et al. [18] determined the optimal RP content for axial compressive intensity, flexural intensity, splitting tension and modulus of elasticity for C80 concrete. In a summary, a certain small amount ($\leq$ 6%) of RP may improve the mechanical characteristics of concrete, but a high RP ($\geq$ 10%) content is unfavorable for its mechanical characteristics and durability. In addition, in the C60~C80 concrete, less investigations reported the maximum content of RP in the concrete.

In practical applications, incorporating steel fibers is one of the ways to improve the characteristics of high-strength concrete, which has been investigated for many years [19–21]. When using steel fibers in concrete, this can hinder the development of macrocracks in the concrete, prevent the growth of microcracks to a macroscopic level and improve the ductility and residual intensity after the formation of the first crack, resulting in greater toughness [22]. As a result, the mechanical characteristics of concrete, such as compressive strength, tensile intensity and modulus of elasticity, can be improved with the content of steel fibers [23]; the aspect ratio of steel fibers has a small effect on the compressive strength of concrete, but a high aspect ratio shows more obvious flexural intensity, compare to a low aspect ratio [22,24]. Bahmani et al. [25] reported that the compressive strength, bending intensity and modulus of elasticity increased in concrete with a content of steel fibers, when the content of RP as a replacement of sand was constant. However, these mechanical characteristics decreased with an increase in the RP content, when the content of steel fibers remained unchanged. Li et al. [26] reported the optimal RP for ultra-high-performance concrete (UHPC) without and with 2 vol.% steel fibers. In general, it can be observed that incorporating steel fibers would improve the mechanical characteristics of concrete and allow us to prepare concrete with a high percentage of RP.

However, note that, at present, the influence of steel fiber content in comparison to RP content on the mechanical characteristics of concrete is mostly studied from an experimental perspective. The average experimental value method [27,28] is normally used to assess the experimental results, resulting in large divergences due to the obvious influences of different RP contents on different mechanical characteristics. In the literature, there is a lack of statistical theory to provide an alternative analysis of the influence of steel fiber content on RP content. It is known that the characteristic value of a mechanical characteristic for concrete has a different meaning compared with the arithmetic average experimental value, and the characteristic value is more scientific. For the concrete design, the characteristic value of a mechanical property is one in its overall distribution, meeting a specified statistical probability to provide a concrete practical testing value equal to or greater than the characteristic value. In China [29], when the characteristic value of the compressive intensity for C50 concrete is 50 MPa, the probability of a practical testing value greater than the characteristic value is 95%. The possibility of the testing value being greater than the characteristic value is 91% in America [30]. Although a comparative approach of experimental arithmetic averages of mechanical characteristics for concrete prepared with various constituents has been considered [27,28], the comparison of characteristic values by means of possibility density distributions is close to real values and meets practical engineering applications [29,30].

Based on the statistical theory, by comparing the characteristic value of mechanical characteristic of steel fiber-reinforced concrete under a high LP with that of concrete under a low LP, it can be observed that the contribution of steel fibers to the mechanical performance's improvement can provide a theoretical foundation for deciding if the engineering application of fiber-reinforced concrete with a high LP content is suitable. Furthermore, it can predict if the mechanical performance loss caused by a high quantity of LP can be compensated by the quantity and type of steel fibers used and how much LP can be used in C80 concrete.

This study first conducts experiments on the fundamental mechanical characteristics of concrete with LP derived from AS (3%, 5%, 7%, 10% and 15%) and that of steel fiber-reinforced concrete with a high LP content (10% and 15%), respectively. Referring to the experimental results and probability theory, the probability density functions of the stochastic variable of the characteristic value of mechanical characteristic for concrete and the difference between stochastic variables of the characteristic values for two types of concretes are developed, which is advanced compared to the arithmetic average comparative approach. By means of the probability of the differences, the contribution of the steel fibers to the concrete's mechanical characteristics prepared with a high content of LP is evaluated, which indicates that the high-strength concrete with a high LP content by incorporating steel fibers could be applied in engineering practices in view of the mechanical properties. Meanwhile, the study provides an evaluation method for other scientific research with a size comparison of any two stochastic physical variables.

2. Materials and Experimental Methods

2.1. Materials in the Study

Ordinary Portland cement (OPC) of P·O 42.5 (produced in Qingzhen, Guizhou, China) was used in the study. Both fine (AS) and coarse natural aggregates (CAs) used to prepare the concrete were locally obtained by crushing natural mountain limestone rock, and the granulometry tests for coarse and fine aggregates are shown in Tables 1 and 2. The fineness modulus of fine aggregate calculated was 3.22, which conforms to the coarse-sand range. The LP was obtained by sieving through the 200-mesh sieve from AS. Its content in concrete was adjusted in accordance with the designed mixture proportions below. In addition, ground-granulated blast-furnace slag powder (GS), fly ash (FA), and silica fume (SF) were used to prepare C80 concrete and their chemical components are shown in Table 3.

In order to improve the mechanical characteristics of concrete with a high amount of LP, three types of steel fiber were used and their main performance indicators with physical properties and length-to-diameter ratios are listed in Table 4. These steel fibers were copper-coated steel (GSF0325, GSF0530) and low-carbon (CGSF07535), as shown in Figure 1.

2.2. Mixture Proportions of Concrete

The optimum mix proportion of C80 concrete obtained by the tests in the laboratory had a water–Thank you for your revised. And we have checked that the intended meaning has been retained cement ratio 0.25, a sand aggregate ratio 0.41 and the quantities of GS, FA and SF were 20%, 10% and 8% for the total cementation material, respectively. The dosage of superplasticizer (high-performance polycarboxylate water reducer) was 1.2%, used to control each type of concrete with a good workability for casting. In the mixture proportions of C80 concrete, as shown in Table 5, the LP content (the mass percentage of LP in AS) was represented by P and a number (e.g., P3 means that the LP content accounts for 3% of the AS mass). Concrete and steel fibers were represented by C and R, respectively. The LP content of concrete and steel fiber concrete were represented by (CP3, CP5 . . .) and (RP10, RP15), respectively (e.g., CP3 means that the LP content accounts for 3% of the AS mass; RP10 means that the LP content accounts for 10% of the AS mass).

Table 1. Granulometry test for fine aggregate.

SZ/mm	SE/g	PS/%	CR/%	TR%
4.75	29.20	5.84	5.84	0~10
2.36	112.60	22.52	28.36	15~37
1.18	116.40	23.28	51.64	37~60
0.60	89.40	17.88	69.52	52~75
0.30	83.40	18.28	86.20	63~85
0.15	55.10	11.02	97.22	70–100
0.075	10.80	2.16	99.38	100
Screen bottom	3.10	0.62	100.00	~

Note: SZ, sieve size; SE, sieve residue; PS, percentage of sieve residue; CR, cumulative percentage of sieve residue; TR, technical requirement.

Table 2. Granulometry test for coarse aggregate.

SZ/mm	SE/g	PS/%	AE/g	CR/%
19 (gravel 2)	9.21	0.46	47.54	0.46
16 (gravel 2)	38.33	1.92	1119.19	2.38
10 (gravel 1)	1071.65	53.58	1942.59	55.96
5 (gravel 1)	823.40	41.17	1999.04	97.17
2.5	56.45	2.82	1999.86	99.95
Screen bottom	0.82	0.04	47.54	2.38

Note: AE, accumulated sieving residue.

Table 3. Chemical components of OPC, GS, FA and SF by wt.%.

Chemical Component	OPC	GS	FA	SF
SiO_2/%	20.210	96.740	56.740	95.560
Al_2O_3/%	4.780	0.320	24.580	0.710
Fe_2O_3/%	2.720	0.080	6.550	0.440
CaO/%	62.140	0.110	6.550	0.680
MgO/%	2.440	0.100	1.860	1.250
Na_2O/%	0.290	0.090	-	-

Table 4. Main performance indicators of steel fibers.

FT	AR	LE/mm	DI/mm	DE/kg/m^3	TS/MPa
GSF0325	83	25	0.3	7850	>2850
GSF0530	60	30	0.5	7850	>2850
CGSF07535	50	25	0.5	7850	>2580

Note: FT, fiber type; AR, aspect ratio; LE, length; DI, diameter; DE, density; TS, tensile strength.

Regarding the influence of steel fibers, their incorporation values of 0.4%, 0.6% and 0.8% by volume were added to CP10 and CP15, respectively to obtain steel fiber-reinforced concrete RP10 and RP15. For example, RP15-R0.4-50 means that the volume of steel fibers was 0.4% and its ratio of length to diameter was 50 in the steel fiber concrete. Additionally, the sample preparation process is shown in Figure 2.

(**a**) GSF0325 fiber (**b**) GSF0530 fiber (**c**) CGSF07535 fiber

Figure 1. Steel fibers physical map.

Table 5. Mixture proportions of C80 concrete (kg/m^3).

CM	CP3	CP5	CP7	CP10	CP15
AS	687.70	673.60	659.40	638.10	602.70
LP	21.30	35.40	49.60	70.90	106.30
CA	1021.00	1021.00	1021.00	1021.00	1021.00
GS	120.00	120.00	120.00	120.00	120.00
FA	60.00	60.00	60.00	60.00	60.00
SF	48.00	48.00	48.00	48.00	48.00
Cement	372.00	372.00	372.00	372.00	372.00
Water	150.00	150.00	150.00	150.00	150.00

Note: CM, concrete mixture; AS, artificial sand; LP, limestone power; CA, coarse aggregate; GS, ground-granulated blast-furnace slag powder; FA, fly ash; SF, silica fume.

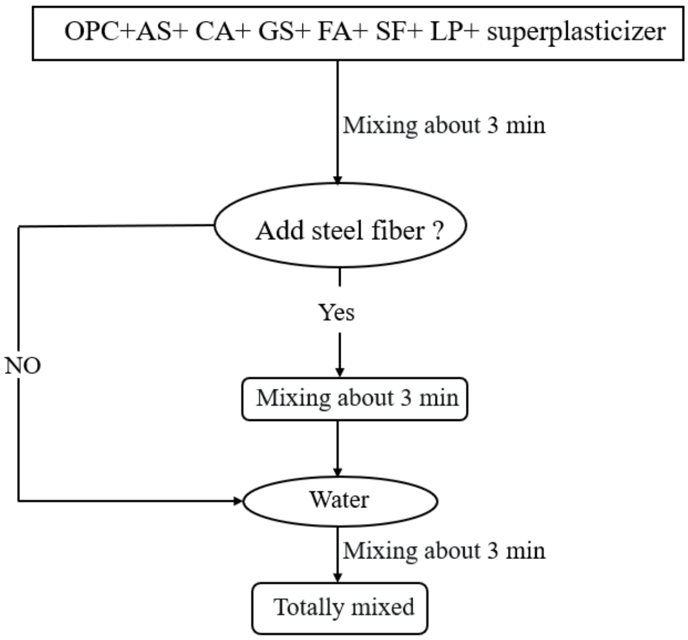


Figure 2. The mixing procedure.

2.3. Experimental Methods

According to the standard [31] and mixture proportions in Table 3, the cubic and prism specimens of 100 × 100 × 100, 100 × 100 × 300 and 100 × 100 × 400 mm were cast. All specimens were cured under standard conditions (temperature 20 ± 2 °C, relative humidity no less than 95%) for 28 days before testing. The axial compressive test and static compression modulus of elasticity (loading instrument [18]) were obtained by measuring the prism sample of 100 × 100 × 300 mm. The flexural test was conducted by a three-point bending measurement, and the test specimen size was 100 × 100 × 400 mm. The split tensile specimen with a size of 100 × 100 × 100 mm was tested by the universal test machine using a load-adding speed of 0.1 MPa s^{-1}. Six specimens were used for each test mentioned above. In the test, the load–deformation curve was automatically recorded by the instrument, and the data acquisition instrument was the Yangzhou Jingming-3813 multifunctional static strain acquisition instrument. The testing set-ups of concrete specimens are shown in Figure 3.

(**a**) Compression or modulus of elasticity test.

(**b**) Flexural test.

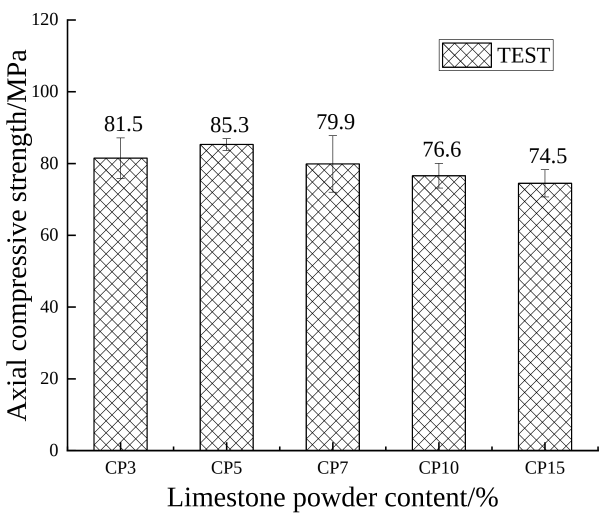
(**c**) Splitting tensile test.

Figure 3. Experimental set-ups.

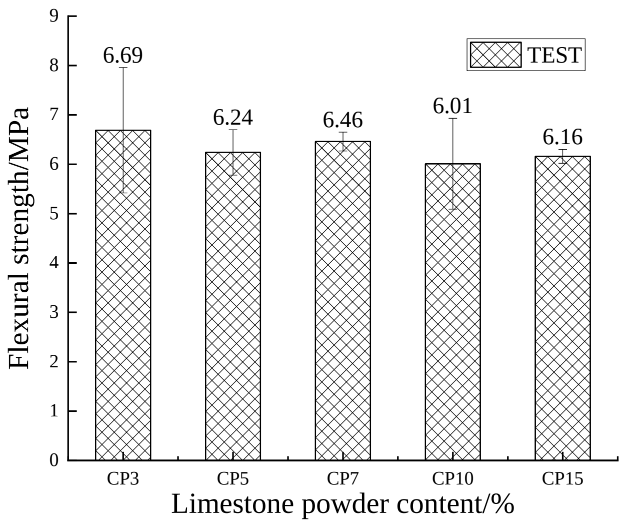
3. Experimental Data and Analysis

3.1. Influence of Different LP Contents on Mechanical Characteristics

Figure 4 shows the average value and standard difference of axial compressive strength, flexural intensity, split tension and modulus of elasticity for concrete prepared with different contents of LP. When the LP content increased from 3% to 5%, the axial compressive and splitting tensile intensity of the concrete had an increasing trend, and then decreased as the LP content changed from 5% to 15%. The flexural intensity and modulus of elasticity obtained the maximum values when the LP content was 3%. In general, a high content of LP up to 15% in the concrete resulted in poor mechanical characteristics. Due to the complicated washing process and its high cost to remove the LP from artificial mountain sand, steel fiber was incorporated into the concrete with a high LP content to improve the performance loss of the mechanical characteristics in this study.

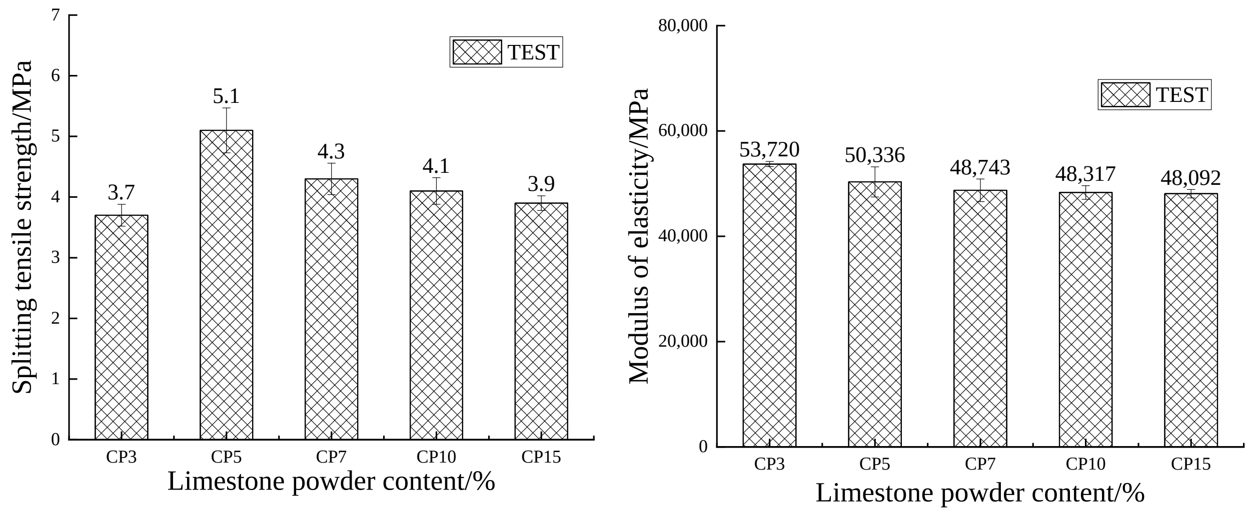


(**a**) Axial compressive intensity.



(**b**) Flexural intensity.

Figure 4. *Cont*.



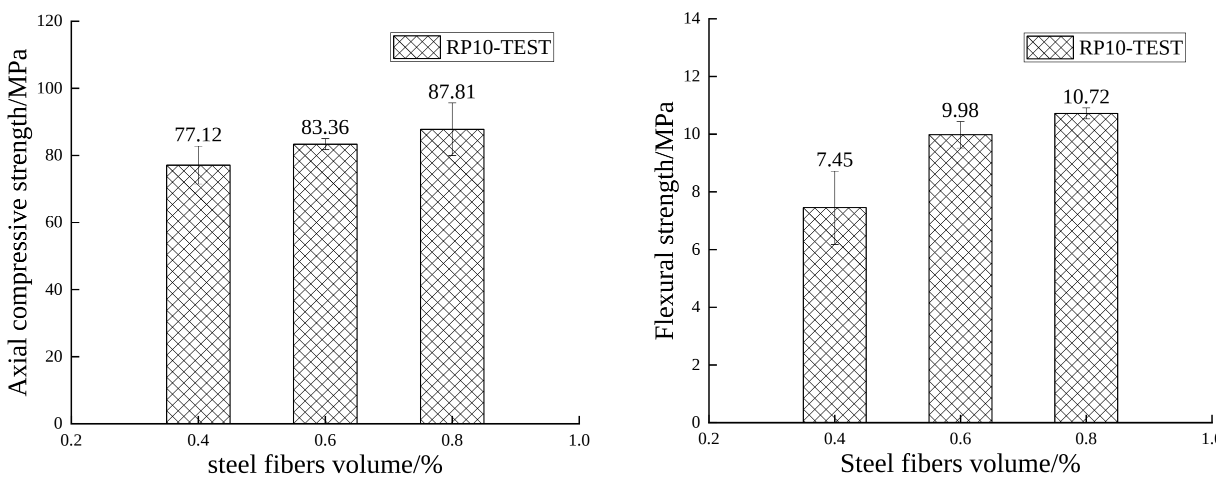
(**c**) Splitting tensile intensity. (**d**) Elastic modulus.

Figure 4. Mechanical characteristics of concrete with different LP contents.

3.2. Influence of Steel Fiber Contents and their Aspect Ratios on Mechanical Properties

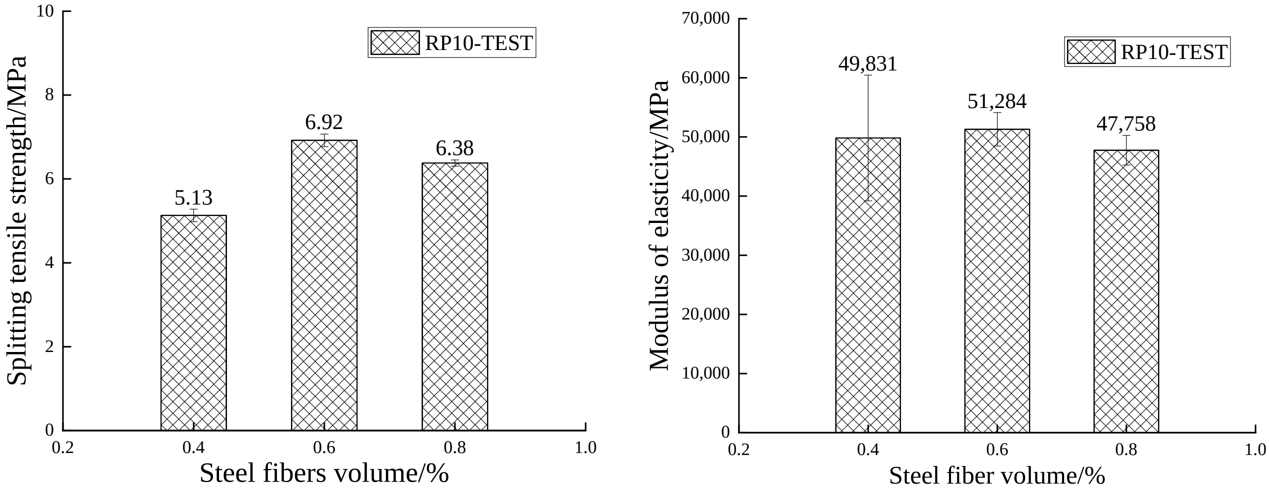
Figure 5 shows the effect of GSF0325 steel fiber contents on the mechanical characteristics of C80 concrete prepared with 10% of LP and the same fiber with a length-to-diameter ratio of 83. According to the experimental results, when the volume fraction for steel fiber increases, the axial compressive and flexural properties of concrete increase; however, its splitting tensile and modulus of elasticity first increase and then decrease.

Figure 6a–d shows the influence of the aspect ratios of steel fibers on the mechanical characteristics of C80 concrete prepared with 15% of LP content and a constant 0.4 vol.% of steel fibers. With an increase in the steel fibers' aspect ratio, the axial compressive strength, flexural intensity, splitting tensile and modulus of elasticity were first slightly increased and then decreased.



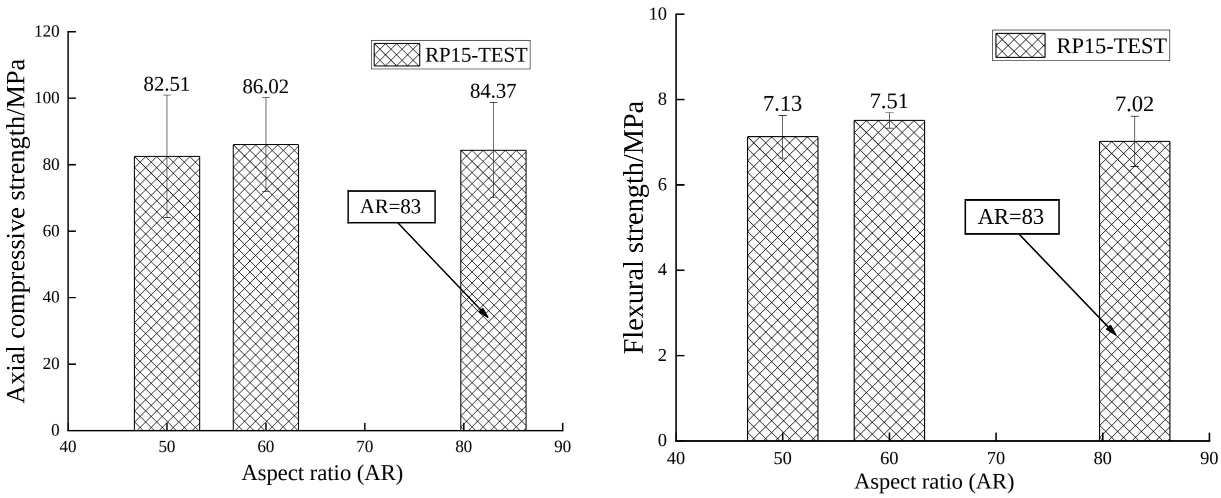
(**a**) Axial compressive intensity. (**b**) Flexural intensity.

Figure 5. *Cont.*

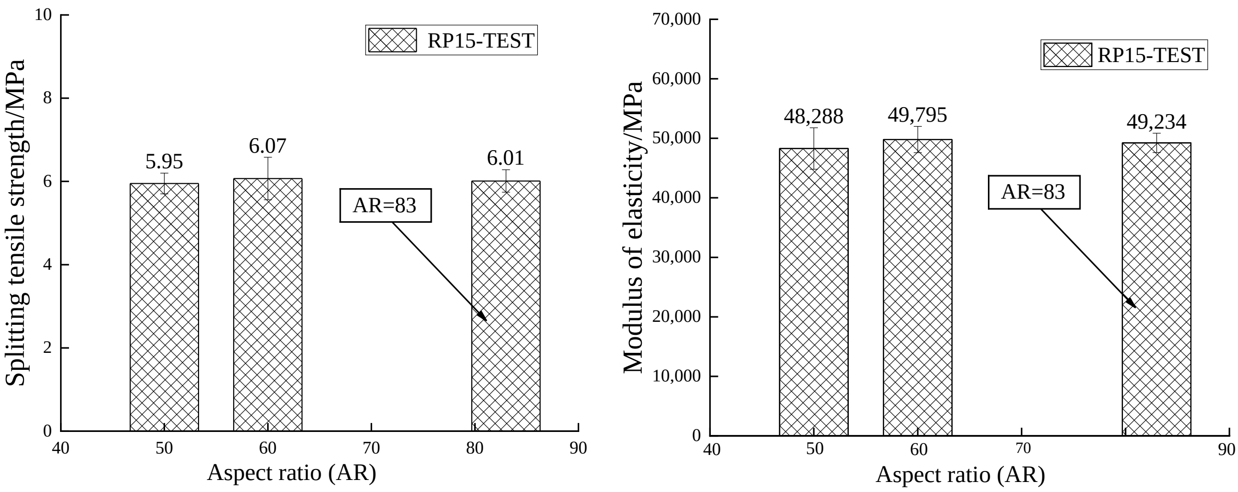


(**c**) Splitting tensile intensity. (**d**) Elastic modulus.

Figure 5. Mechanical characteristics of concrete with 10% LP incorporating different steel fiber GSF0325 contents.



(**a**) Axial compressive intensity. (**b**) Flexural intensity.



(**c**) Splitting tensile intensity. (**d**) Elastic modulus.

Figure 6. Mechanical characteristics of concrete with 15% LP with different steel fiber length-to-diameter ratios.

In general, the increase in the amount of steel fibers can not only increase the flexural intensity and ductility of concrete, but can also increase the axial compressive intensity, which could be the reason that the high LP content padded the gap resulting from the addition of steel fibers.

Note that when analyzing these experimental data, the arithmetic average value has obvious discreteness (i.e., different standard deviations) and it is hard to confirm the steel fiber content and its type for compensating for the mechanical characteristics of concrete with 10% and 15% LP values.

4. Development of a Statistical Method

In this study, the probability density functions of the stochastic variable for the characteristic value and the difference between the stochastic variables of the two characteristic values were derived by mathematical statistics. When the probability that the stochastic variable of the characteristic value of a mechanical characteristic for concrete prepared with steel fiber and a high LP content is higher than concrete prepared with a low LP content, which meets required criterion, the steel fiber used can make up for the loss of mechanical characteristics of concrete due to its high LP content.

The symbols and meanings used in the following text are shown in Table 6. According to the mathematical statistics, the main thoughts to develop the probability density functions of the stochastic variable of the characteristic value and the difference between the stochastic variables of two characteristic values are presented below. First, the dimensional stochastic variables G and R are transformed into dimensionless stochastic variables A and B to facilitate the consistent presentation of the results, respectively. According to the definition of the probability density function, these functions of the sample standard difference of stochastic variables G, R, A and B are derived. In line with the formula of the characteristic value of mechanical characteristic of concrete, the stochastic variables Z_a, Z_b are constructed from the characteristic value of stochastic variable A with $1-\alpha_a$ assurance factor and that of stochastic variable B with $1-\alpha_b$ assurance factor, respectively. Then, the probability density function of the difference between the two stochastic variables Z_b and Z_a is derived, obtaining the probability $P\{Z_b > Z_a\}$ of $Z_b > Z_a$. Similarly, stochastic variables Z_g and Z_r from the characteristic value of stochastic variable G with $1-\alpha_a$ assurance factor and that of stochastic variable R with $1-\alpha_b$ assurance factor are constructed, respectively. It can obtain the probability $P\{Z_r > Z_g\}$ of $Z_r > Z_g$ from $P\{Z_r > Z_g\} = P\{Z_b > Z_a\}$ (that is, the probability that the characteristic value of stochastic variable R with $1-\alpha_b$ assurance factor is greater than that of stochastic variable G with $1-\alpha_a$ assurance factor).

The theoretical derivation detail of the mathematical statistics and its verification are shown in the Supplementary Materials (Table S1). The main theoretical derivation is presented below.

In the following formulas, it is assumed that the value of the standard difference is equal to the value of the sample standard difference for the same stochastic variable. Define the sample average's ratio and variation coefficients of stochastic variables R and G, respectively, as follows:

$$\begin{cases} C = \mu_r/\mu_g \\ \delta_i = S_i/\mu_i, (i = g, r) \end{cases} \tag{1}$$

In order to facilitate the consistent presentation of the results, assuming that μ_g and μ_r are known, the dimensional stochastic variables G and R are transformed into dimensionless stochastic variables A and B, respectively, as follows:

$$A : a_i = g_i/[0.5(\mu_g + \mu_r)], (i = 1, 2, \cdots\cdots, n_g) \tag{2}$$

$$B : b_i = r_i/[0.5(\mu_g + \mu_r)], (i = 1, 2, \cdots\cdots, n_r) \tag{3}$$

Table 6. Symbols and meanings.

Symbols	Meanings
G, R	Stochastic variables G ($G: G_1, G_2, \ldots, G_{n_g}$) and R ($R: R_1, R_2, \ldots, R_{n_r}$) obey the normal distribution and represent the experimental test data of concrete and steel fiber-reinforced concrete, respectively.
A, B	Dimensionless stochastic variables.
$\mu_g, \mu_r, \mu_a, \mu_b$	Sample average of stochastic variables G, R, A and B.
$\sigma_g, \sigma_r, \sigma_a, \sigma_b$	Standard difference of stochastic variables G, R, A and B.
S_a, S_b, S_g, S_r	Sample standard difference.
Z_g and Z_a, Z_r and Z_b	Stochastic variable of characteristic value with $1-\alpha_a$ and $1-\alpha_b$ assurance factors for stochastic variables G and A, and R and B, respectively.
k_a, k_b	Upper α_a and α_b fractiles of standard normal distributions for stochastic variables G and A, and R and B, respectively.
n_g, n_r	Sample sequences of stochastic variables G, R.
$\Gamma(g)$	$\int_0^{+\infty} t^{g-1}e^{-t}dt,\ g \in (0,+\infty)$.
δ_i	$S_i/\mu_i, (i = g, r)$.
$C = \mu_r/\mu_g$	Ratios of G, R for sample averages.

The average and sample variance of stochastic variables A and B are:

$$\begin{cases} \mu_a = 2/(1+C) \\ S_a^2 = 4\delta_g^2/(1+C)^2 \end{cases} \tag{4}$$

$$\begin{cases} \mu_b = 2C/(1+C) \\ S_b^2 = 4C^2\delta_r^2/(1+C)^2 \end{cases} \tag{5}$$

Thus, the characteristic values of stochastic variables G, R, A and B are as follows:

$$\begin{cases} \mu_i - k_j\sigma_i, (i = g, j = a;\ i = r, j = b) \\ \mu_l - k_l\sigma_l,\ (l = a, b) \end{cases} \tag{6}$$

Define the average of stochastic variables A and B, respectively, as:

$$\overline{a} = \sum_{i=1}^{n_g} a_i \Big/ n_g \tag{7}$$

$$\overline{b} = \sum_{i=1}^{n_r} b_i \Big/ n_r \tag{8}$$

Through the characteristic values of stochastic variables A and B defined by Equation (6), two new stochastic variables are defined, respectively, as:

$$Z_a = \overline{a} - k_a S_a/M_a \tag{9}$$

$$Z_b = \overline{b} - k_b S_b/M_b \tag{10}$$

where $M_i = \sqrt{2}\Gamma(0.5n_j)/[\sqrt{n_j - 1}\Gamma(0.5n_j - 0.5)]$, $(i = a, j = g;\ i = b, j = r)$. Yield that the average values $E(Z_a)$ and $E(Z_b)$ of stochastic variables Z_a and Z_b are the unbiased estimations of Equation (6), respectively.

Then, the probability density functions of Z_a and Z_b are as follows:

$$f_{Z_a}(z) = H_a \int_0^{\infty} S^{n_g - 2} e^{-\frac{1}{2\sigma_a^2}\left[n_g(k_a S/M_a + z - \mu_a)^2 + (n_g - 1)S^2\right]} dS \tag{11}$$

$$f_{Z_b}(z) = H_b \int_0^{\infty} S^{n_r-2} e^{-\frac{1}{2\sigma_b^2}[n_r(k_b S/M_b + z - \mu_b)^2 + (n_r-1)S^2]} dS \quad (12)$$

where $H_i = \sqrt{\frac{2n_j}{\pi}} \frac{(\frac{n_j-1}{2})^{\frac{n_j-1}{2}}}{\sigma_i^{n_j}\Gamma(\frac{n_j-1}{2})}, (i = a, j = g; i = b, j = r)$. Due to the independence of stochastic variables Z_a and Z_b, the probability density and distribution functions of stochastic variable $Z_c = Z_b - Z_a$ are expressed as follows:

$$f_{Z_c}(u) = \int_{-\infty}^{\infty} f_{Z_a}(Z_b - u) f_{Z_b}(Z_b) dZ_b \quad (13)$$

$$F_{Z_c}(z) = \int_{-\infty}^{z} f_{Z_c}(u) du \quad (14)$$

Based on these equations, the probability of $Z_c > Z_\alpha$ (Z_α is any real number data) can be obtained as follows:

$$P\{Z_c > Z_\alpha\} = 1 - P\{Z_c \le Z_\alpha\} = 1 - F_{Z_c}(Z_\alpha) \quad (15)$$

Through the characteristic values of stochastic variables G and R defined by Equation (6), two new stochastic variables are defined, respectively, as:

$$\begin{cases} Z_g = \overline{g} - k_a S_g / M_g \\ \overline{g} = \sum_{i=1}^{n_g} g_i \Big/ n_g \end{cases} \quad (16)$$

$$\begin{cases} Z_r = \overline{r} - k_b S_r / M_r \\ \overline{r} = \sum_{i=1}^{n_r} r_i \Big/ n_r \end{cases} \quad (17)$$

where $M_g = M_a$ and $M_r = M_b$. Yield that the average values $E(Z_g)$ and $E(Z_r)$ of stochastic variables Z_g and Z_r are the unbiased estimations of Equation (6), respectively.

When Z_α is a positive number and approaches 0, the probability that characteristic value of stochastic var. R is greater than that of stochastic var. G is:

$$P\{Z_r > Z_g\} = P\{Z_b > Z_a\} = 1 - P\{Z_c \le Z_\alpha\} = 1 - F_{Z_c}(Z_\alpha) \quad (18)$$

5. Results

According to the calculations in the Supplementary Materials (Tables S2–S4, Figures S1–S3), it can be found that when $P\{Z_r > Z_g\} < 0.5$, the characteristic value of stochastic var. R is smaller than that of stochastic var. G. When $P\{Z_r > Z_g\} > 0.5$, the characteristic value of stochastic var. R is greater than that of stochastic var. G.

In this study, the concrete prepared with a high LP content and a certain amount of steel fibers used, and the one only prepared with a low LP content were paired into a group. For comparison, the probability that the characteristic value of each mechanical characteristic of concrete prepared with steel fibers was higher than that of concrete prepared with a low LP content is considered higher than 0.5, which then shows that the steel fiber used can compensate the mechanical performance loss due to the high LP content.

A paired group of RP10-R0.6-83 and CP7 was taken as an example and descriptions are presented as follows: RP10-R0.6-83 was a steel fiber-reinforced concrete prepared with 10 wt.% of LP content, a 0.6 vol.% of steel fiber content and an 83 length-to-diameter ratio. Additionally, the experimental results for axial compressive strength, flexural intensity, splitting tension intensity and modulus of elasticity of RP10-R0.6-83 are defined as stochastic variables R_1, R_2, R_3 and R_4, respectively. Due to the six sample tests for each mechanical characteristic of steel fiber concrete, $n_{r1} = n_{r2} = n_{r3} = n_{r4} = 6$. According to [9], the characteristic value of each mechanical characteristic for concrete has a 95% assurance factor, namely, $k_{b1} = k_{b2} = k_{b3} = k_{b4} = 1.645$. Additionally, stochastic variables Z_{r1},

Z_{r2}, Z_{r3} and Z_{r4} are obtained according to Equation (17), respectively. P7 was a concrete prepared with 7% of LP content. The test results for axial compression, flexural property, splitting tension and modulus of elasticity are defined as stochastic variables G_1, G_2, G_3 and G_4, respectively, and their intensity value rule is consistent with the abovementioned steel fiber concrete, that is, $k_{a1} = k_{a2} = k_{a3} = k_{a4} = 1.645$. Finally, the stochastic variables Z_{g1}, Z_{g2}, Z_{g3} and Z_{g4} are obtained by Equation (16), respectively. When all four probabilities of $P\{Z_{r1} > Z_{g1}\} > 0.5$, $P\{Z_{r2} > Z_{g2}\} > 0.5$, $P\{Z_{r3} > Z_{g3}\} > 0.5$ and $P\{Z_{r4} > Z_{g4}\} > 0.5$ are established, it is then considered that incorporating 0.6 vol. % of steel fiber and its aspect ratio of 83 can compensate for the mechanical performance loss due to the increase in LP from 7% to 10%. Therefore, by adopting such a steel fiber, the mechanical characteristics of concrete with 10% LP content can reach the levels of concrete prepared with a 7% LP content.

In Tables 7–11, RP10 and CP3, CP5 and CP7 were further paired up into three batches from batches 1 to 3 and RP15, and CP3, CP5, CP7 and CP10 were paired up into four batches from batches 4 to 7, as shown in Tables 8–11. In every batch, three comparisons between three types of steel fiber concrete and one type of concrete were performed, respectively. Furthermore, the experimental data for axial compression, flexural intensity, splitting tension intensity and modulus of elasticity for concrete and steel fiber concrete in each comparison were defined as stochastic variables G_1, G_2, G_3 and G_4, and R_1, R_2, R_3 and R_4, respectively. From batches 1 to 7, the calculating results $P\{Z_{r1} > Z_{g1}\}$, $P\{Z_{r2} > Z_{g2}\}$, $P\{Z_{r3} > Z_{g3}\}$ and $P\{Z_{r4} > Z_{g4}\}$ and the average of these four probabilities in each comparison are listed in Tables 7–13.

Table 7. Probability that the CVMC for steel fiber concrete is greater that of concrete for batch 1.

Comparison Item for Batch 1	**CP3**		
	RP10-R0.4-83	**RP10-R0.6-83**	**RP10-R0.8-83**
ACS $P\{Z_{r1} > Z_{g1}\}$	0.2024	0.8890	0.6571
FS $P\{Z_{r2} > Z_{g2}\}$	0.7343	0.9997	0.9999
STS $P\{Z_{r3} > Z_{g3}\}$	1.0000	1.0000	1.0000
EM $P\{Z_{r4} > Z_{g4}\}$	0.0017	0.0009	0.0004

Note: CVMC, characteristic value of mechanical characteristic; ACS, axial compressive intensity; FS, flexural intensity; STS, splitting tensile intensity; EM, elastic modulus.

Table 8. Probability that the CVMC for steel fiber concrete is greater than that of concrete used for batch 2.

Comparison Item for Batch 2	**CP5**		
	RP10-R0.4-83	**RP10-R0.6-83**	**RP10-R0.8-83**
ACS $P\{Z_{r1} > Z_{g1}\}$	0.0969	0.0969	0.0673
FS $P\{Z_{r2} > Z_{g2}\}$	0.4525	0.9999	0.9999
STS $P\{Z_{r3} > Z_{g3}\}$	0.8244	0.9999	1.0000
EM $P\{Z_{r4} > Z_{g4}\}$	0.0302	0.6364	0.2116

In Tables 7–13, the characteristic value of each mechanical characteristic of RP10-R0.6-83 was greater than that of CP7. Therefore, it can be considered that the mechanical characteristics of RP10-R0.6-83 can reach the mechanical characteristics of CP7, that is, in the concrete prepared with 10% of LP content, R0.6-83 can compensate for the mechanical performance loss due to the increase in LP from 7% to 10%.

Table 9. Probability that the CVMC for steel fiber concrete is greater that of concrete used for batch 3.

Comparison Item for Batch 3	CP7		
	RP10-R0.4-83	RP10-R0.6-83	RP10-R0.8-83
ACS $P\{Z_{r1} > Z_{g1}\}$	0.5446	0.9956	0.8531
FS $P\{Z_{r2} > Z_{g2}\}$	0.1798	0.9999	0.9999
STS $P\{Z_{r3} > Z_{g3}\}$	0.9998	1.0000	1.0000
EM $P\{Z_{r4} > Z_{g4}\}$	0.0324	0.7182	0.2338

Table 10. Probability that the CVMC for steel fiber concrete is greater that of concrete used for batch 4.

Comparison Item for Batch 4	CP3		
	RP15-R0.4-50	RP15-R0.4-60	RP15-R0.4-83
ACS $P\{Z_{r1} > Z_{g1}\}$	0.7626	0.9179	0.2489
FS $P\{Z_{r2} > Z_{g2}\}$	0.9973	0.9829	0.9633
STS $P\{Z_{r3} > Z_{g3}\}$	1.0000	0.9985	0.9999
EM $P\{Z_{r4} > Z_{g4}\}$	0.0008	0.0016	0.0008

Table 11. Probability that the CVMC for steel fiber concrete is greater that of concrete used for batch 5.

Comparison Item for Batch 5	CP5		
	RP15-R0.4-50	RP15-R0.4-60	RP15-R0.4-83
ACS $P\{Z_{r1} > Z_{g1}\}$	0.0071	0.1089	0.0099
FS $P\{Z_{r2} > Z_{g2}\}$	0.9999	0.9795	0.9395
STS $P\{Z_{r3} > Z_{g3}\}$	0.9905	0.8692	0.9899
EM $P\{Z_{r4} > Z_{g4}\}$	0.1499	0.5772	0.6513

Table 12. Probability that the CVMC for steel fiber concrete is greater that of concrete used for batch 6.

Comparison Item for Batch 6	CP7		
	RP15-R0.4-50	RP15-R0.4-60	RP15-R0.4-83
ACS $P\{Z_{r1} > Z_{g1}\}$	0.9296	0.9781	0.4882
FS $P\{Z_{r2} > Z_{g2}\}$	0.9999	0.8715	0.5559
STS $P\{Z_{r3} > Z_{g3}\}$	0.9995	0.9029	0.9998
EM $P\{Z_{r4} > Z_{g4}\}$	0.1624	0.6720	0.7663

Table 13. Probability that the CVMC for steel fiber concrete is greater that of concrete used for batch 7.

Comparison Item for Batch 7	CP10		
	RP15-R0.4-50	RP15-R0.4-60	RP15-R0.4-83
ACS $P\{Z_{r1} > Z_{g1}\}$	0.9001	0.9812	0.2880
FS $P\{Z_{r2} > Z_{g2}\}$	0.9999	0.9979	0.9941
STS $P\{Z_{r3} > Z_{g3}\}$	0.9999	0.9480	0.8666
EM $P\{Z_{r4} > Z_{g4}\}$	0.0661	0.4965	0.6302

Similarly, the characteristic value of each mechanical characteristic of RP15-R0.4-60 was greater than that of the mechanical characteristic of CP7. Therefore, the mechanical characteristics of RP15-R0.4-60 can reach the mechanical characteristics of CP7, that is, in the concrete prepared with 15% of LP content, R0.4-60 can compensate for the mechanical performance loss due to the increase in LP from 7% to 15%.

6. Discussion

At present, the comparative method of arithmetic averages of fundamental mechanical characteristics for concrete prepared with various constituents is the main method [27,28]. From the method, in the experimental test results, as shown in Table 14, the axial compressive intensity of RP10-R0.4-83 is less than that of CP3, CP5 and CP7; its flexural intensity is greater than that of CP3, CP5 and CP7; its splitting tensile strength is greater than that of CP3, CP5 and CP7, and its elastic modulus is greater than that of CP7 and less than that of CP3 and CP5. Therefore, R0.4-83 cannot offset the loss of mechanical characteristics for concrete when increasing the LP content from 3% to 10%, 5% to 10% and 7% to 10%, respectively. Similarly, R0.8-83 and R0.4-50 cannot offset the loss of mechanical characteristics for concrete when the LP content is 10% and 15%, respectively. However, the axial compressive intensity of RP10-R0.6-83 was greater than that of CP3 and CP7, its flexural intensity was greater than that of CP3, CP5 and CP7, its splitting tensile strength was greater than that of CP3, CP5 and CP7, and its elastic modulus was greater than that of CP5 and CP7. Therefore, R0.6-83 can offset the loss of mechanical characteristics for concrete with the increase in LP content from 7% to 10%. However, both R0.4-60 and R0.4-83 can offset the loss of mechanical characteristics for concrete when increasing of LP content from 7% to 15% and 10% to 15%.

Table 14. Average value and standard difference of mechanical characteristics of concrete and steel fiber concrete.

CS	ACS		FS		STS		EM	
	AV/MPa	SD/MPa	AV/MPa	SD/MPa	AV/MPa	SD/MPa	AV/MPa	SD/MPa
CP3	81.5	5.65	6.69	1.27	3.70	0.18	53,720	495.03
CP5	85.3	1.64	6.24	0.46	5.10	0.37	50,336	2859.03
CP7	79.9	7.87	6.46	0.19	4.30	0.26	48,743	2149.06
CP10	76.6	3.42	6.01	0.92	4.10	0.22	48,317	1306.82
RP10-R0.4-83	77.1	5.65	7.45	1.27	5.13	0.15	49,831	10,632.20
RP10-R0.6-83	83.4	1.64	9.98	0.46	6.92	0.15	51,284	2831.61
RP10-R0.8-83	87.8	7.87	10.72	0.19	6.38	0.075	47,758	2499.77
RP15-R0.4-50	82.5	4.15	7.13	0.18	5.95	0.25	48,288	3488.51
RP15-R0.4-60	86.0	4.34	7.51	0.59	6.07	0.51	49,795	2200.50
RP15-R0.4-83	84.4	10.75	7.02	0.50	6.01	0.27	49,234	1615.18

Note: CS, concrete and steel fiber concrete; AV, average value; SD, standard difference.

However, only by considering the mean values of fundamental mechanical characteristics for concrete and steel fiber concrete in the comparative method of arithmetic average, the method could be misjudged for the offset of mechanical characteristics in engineering applications. The standard difference is the shift of the test data from the average value; therefore, both the mean value and standard difference should be considered to determine the quantity and type of steel fiber used and the amount of LP that can be maximally allowed to be used in C80 concrete. According to the method presented in this paper, R0.6-83 can compensate for the loss of mechanical characteristics for concrete when increasing the LP content from 7% to 10%, which is in accord with the results of the arithmetic average method to verify the correctness of the method presented. Nevertheless, owing to the high dispersions of axial compressive intensity of RP15-R0.4-83 (standard difference 10.75 MPa) and elastic modulus of RP15-R0.4-60 (standard difference 2200.50 MPa), by using the arithmetic average method, it is misjudged that R0.4-83 and R0.4-60 can compensate for the loss of mechanical characteristics for concrete when increasing the LP content from 7% to 15% and 10% to 15%, and when the increasing the LP content from 10% to 15%, respectively.

Therefore, the comparative method for the arithmetic average of mechanical characteristics is not defective for engineering applications due to not considering the effect of the standard difference. However, the comparative method for characteristic values of mechanical characteristics for concrete presented in this paper can consider the influence of the average value and standard difference on the mechanical characteristics, which is scientific for the engineering applications of concrete with a high LP content.

7. Conclusions

In this study, the influence of LP content (3–15%) on the basic mechanical characteristics of C80 concrete prepared with AS was firstly evaluated experimentally, and then the addition of steel fibers to improve the mechanical performance of C80 concrete with a high LP content (10% and 15%) was analyzed. To scientifically analyze the influence of steel fibers, the mechanical characteristics of concrete were assessed based on the mathematical statistics theory, and the probability density functions of the stochastic variable of its characteristic value and the difference between stochastic variables of two characteristic values were derived.

When increasing the LP in concrete over 5%, it can influence axial compression, bending property, splitting tension and modulus of elasticity, in particular, there was an obvious decrease in the axial compressive property, splitting tension and modulus of elasticity. However, incorporating steel fibers is a way to compensate for its mechanical performance loss.

In civil engineering, for concrete design, the mean value of the experimental data for concrete was not used, but the mechanical characteristic value of concrete was. When analyzing these experimental data from the mechanical characteristics by the comparative method of arithmetic averages, there was a deviation between the arithmetical mean and characteristic value.

The theoretical derivation developed can be used to compare characteristic values of two stochastic concrete mix ratios in the same batch of the experimental range. Using the method in the paper, the characteristic value of stochastic var. R was more than that of stochastic var. G, when the probability that the stochastic variable of the characteristic value for stochastic var. R in the experimental test was greater than that for stochastic var. G in the experimental test, which was greater than 0.5.

In the concrete prepared with 10% of LP, the steel fibers of SF-0.6-83 used could compensate for the mechanical performance loss due to the increase in LP from 7% to 10%. Additionally, in the concrete prepared with 15% of LP, the steel fibers of SF-0.4-60 used could contribute to the performance loss due to the increase in LP from 7% to 15%.

Although the study demonstrates that the high-strength concrete with a high LP and steel fiber content can be applied to civil engineering practices in the view of mechanical properties, the concrete's durability needs to be investigated in the future to verify the feasibility on large-scale applications of concrete.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13030602/s1, Table S1 Symbols and Meanings; Table S2 $Z_g > Z_r$; Table S3 $Z_g = Z_r$; Table S4 $Z_g < Z_r$; Figure S1 When $Z_g > Z_r$, the possibility density function $f_{Z_c}(u)$ of Z_c; Figure S2 When $Z_g = Z_r$, the possibility density function $f_{Z_c}(u)$ of Z_c; Figure S3 When $Z_g < Z_r$, the possibility density function $f_{Z_c}(u)$ of Z_c. Reference [1] is cited in the Supplementary Materials file.

Author Contributions: Experiment development, manuscript writing, data analysis, article composition, Q.X.; innovation refining, quality control, grammar proofreading, D.X.; quality control, formula derivation, data proofreading, B.S.; quality control, data verification, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: The funding projects for this paper were the Natural Science Research Project of Guizhou Provincial Department of Education (No. SY [2012] 3067) and the Natural Science Foundation of Guizhou Province (No. [2015] 364 and [2018] 1038).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the results of this study are available.

Acknowledgments: We are grateful to those involved in this work.

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

References

1. He, H.; Wang, Y.; Wang, J. Compactness and hardened properties of machine-made sand mortar with aggregate micro fines. *Constr. Build. Mater.* **2020**, *250*, 118828. [CrossRef]
2. Shi, L.H.; Ma, H.X. Experimental Study on Effect of Limestone Powder on Concrete Properties in Mechanism Sand. *Integr. Ferroelectr.* **2021**, *215*, 38–46. [CrossRef]
3. *DB 24/016-2010*; Technical Specification of Rock Sand Concrete. Local Standard of Guizhou Province. People's Republic of China: Guizhou, China, 2010. (In Chinese)
4. *JGJ 52-2006*; Standard for Technical Requirements and Test Method of Sand and Crushed Stone (or Gravel) for Ordinary Concrete. China Building Industry Press: Beijing, China, 2006.
5. Choudhary, R.; Gupta, R.; Nagar, R. Impact on fresh, mechanical, and microstructural properties of high strength self-compacting concrete by marble cutting slurry waste, fly ash, and silica fume. *Constr. Build. Mater.* **2020**, *239*, 117888. [CrossRef]
6. Li, L.G.; Huang, Z.H.; Tan, Y.P.; Kwan, A.K.H.; Chen, H.Y. Recycling of marble dust as paste replacement for improving strength, microstructure and eco-friendliness of mortar. *J. Clean. Prod.* **2019**, *210*, 55–65. [CrossRef]
7. Ma, B.; Wang, J.; Tan, H.; Li, X.; Cai, L.; Zhou, Y.; Chu, Z. Utilization of waste marble powder in cement-based materials by incorporating nano silica. *Constr. Build. Mater.* **2019**, *211*, 139–149. [CrossRef]
8. El-Sayed, H.A.; Farag, A.B.; Kandeel, A.M.; Younes, A.A.; Yousef, M.M. Characteristics of the marble processing powder waste at Shaq El-Thoaban industrial area, Egypt, and its suitability for cement manufacture. *HBRC J.* **2019**, *14*, 171–179. [CrossRef]
9. Ashish, D.K. Concrete made with waste marble powder and supplementary cementitious material for sustainable development. *J. Clean. Prod.* **2019**, *211*, 716–729. [CrossRef]
10. Febin, G.K.; Abhirami, A.; Vineetha, A.K.; Manisha, V.; Ramkrishnan, R.; Sathyan, D.; Mini, K.M. Strength and durability properties of quarry dust powder incorporated concrete blocks. *Constr. Build. Mater.* **2019**, *228*, 116793. [CrossRef]
11. Rathan, R.; Sunitha, V. Mechanical and microstructural study on interlocking concrete block pavers using waste granite dust. *Int. J. Pavement Eng.* **2022**, *23*, 358–371. [CrossRef]
12. Zhang, K.Q.; Liu, F.S.; Yue, Q.; Feng, J.G. Effect of granite powder on properties of concrete. *Asia-Pac. J. Chem. Eng.* **2020**, *15*, e2468. [CrossRef]
13. Xie, K.Z.; Bai, M.Y.; Qing, Z.G.; Li, J.; Ge, B.Z. Study on Durability of Manufactured Sand Based on Stone Powder Content. *Sci. Adv. Mater.* **2018**, *10*, 1608–1614. [CrossRef]
14. Tang, Y.; Qiu, W.C.; Liu, D.W.; Zhang, W.M.; Zhang, R.P. Experimental Study on the Properties of Mortar and Concrete Made with Tunnel Slag Machine-Made Sand. *Materials* **2022**, *15*, 4817. [CrossRef]
15. Shen, W.G.; Liu, Y.; Wang, Z.W.; Cao, L.H.; Wu, D.L.; Wang, Y.J.; Ji, X.L. Influence of manufactured sand's characteristics on its concrete performance. *Constr. Build. Mater.* **2018**, *172*, 574–583. [CrossRef]
16. Fu, T.; Liang, J.L.; Lan, Y.F.; Xiao, Y.P.; Wei, J.H. Effect of Stone Powder Content on Mechanical Properties of Manufactured Sand Concrete. *Iran. J. Sci. Technol.-Trans. Civ. Eng.* **2022**, *46*, 4255–4264. [CrossRef]
17. Zheng, S.Y.; Liang, J.L.; Hu, Y.J.; Wei, D.Y.; Lan, Y.F.; Du, H.L.; Rong, H.L. An experimental study on compressive properties of concrete with manufactured sand using different stone powder content. *Ferroelectrics* **2021**, *579*, 189–198. [CrossRef]
18. Wu, H.M.; Shen, B.; Ma, K.J.; Xuan, D.X. Assessment of mechanical properties of C80 concrete prepared with different stone powder contents by a statistical analysis. *J. Build. Eng.* **2022**, *56*, 104754. [CrossRef]
19. Jang, S.J.; Yun, H.D. Combined effects of steel fiber and coarse aggregate size on the compressive and flexural toughness of high-strength concrete. *Compos. Struct.* **2018**, *185*, 203–211. [CrossRef]
20. Khan, M.I.; Abbass, W. Effect of Hybridization of steel fibers on the mechanical properties of high strength concrete. In Proceedings of the 5th International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, 19–21 November 2018.
21. Mastali, M.; Dalvand, A.; Sattarifard, A.R.; Abdollahnejad, Z.; Illikainen, M. Characterization and optimization of hardened properties of self-consolidating concrete incorporating recycled steel, industrial steel, polypropylene and hybrid fibers. *Compos. Part B Eng.* **2018**, *151*, 186–200. [CrossRef]
22. Abbass, W.; Khan, M.I.; Mourad, S. Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete. *Constr. Build. Mater.* **2018**, *168*, 556–569. [CrossRef]
23. Kim, K.C.; Yang, I.H.; Joh, C. Effects of Single and Hybrid Steel Fiber Lengths and Fiber Contents on the Mechanical Properties of High-Strength Fiber-Reinforced Concrete. *Adv. Civ. Eng.* **2018**, *2018*, 7826156. [CrossRef]
24. Yang, G.Y.; Wei, J.X.; Yu, Q.J.; Huang, H.L.; Li, F.X. Investigation of the Match Relation between Steel Fiber and High-Strength Concrete Matrix in Reactive Powder Concrete. *Materials* **2019**, *12*, 1751. [CrossRef] [PubMed]

25. Bahmani, H.; Mostofinejad, D.; Dadvar, S.A. Mechanical Properties of Ultra-High-Performance Fiber-Reinforced Concrete Containing Synthetic and Mineral Fibers. *ACI Mater. J.* **2020**, *117*, 155–168. [CrossRef]
26. Li, P.P.; Yu, Q.L.; Brouwers, H.J.H. Effect of coarse basalt aggregates on the properties of Ultra-high Performance Concrete (UHPC). *Constr. Build. Mater.* **2018**, *170*, 649–659. [CrossRef]
27. Li, T.; Fan, H.; García, J.; Corchado, J.M. Second-order statistics analysis and comparison between arithmetic and geometric average fusion: Application to multi-sensor target tracking. *Inf. Fusion* **2019**, *51*, 233–243. [CrossRef]
28. Quiroz, J.; Montes, R.; Shi, H.L.; Roychoudhury, S. A comparative study of confidence intervals to assess biosimilarity from analytical data. *Pharm. Stat.* **2019**, *18*, 316–328. [CrossRef]
29. *GB/T 50107-2010*; Standard for Evaluation of Concrete Compressive Strength. China Building Industry Press: Beijing, China, 2010. (In Chinese)
30. *ACI 318-19*; Building Code Requirements for Structural Concrete. American Concrete Institute: Farmington Hills, MI, USA,, 2019.
31. *GB/T 50081-2019*; Standard for Test Method of Physical and Mechanical Properties of Concrete. China Building Industry: Beijing, China, 2019. (In Chinese)