Investigation of Impact Resistance of High-Performance Polypropylene Fiber-Reinforced Recycled Aggregate Concrete

Tingting Zhang 1, Bojian Wu 1, Xiangqing Kong 1,2,* and Ying Fu 2

1 Department of Civil & Architectural, Liaoning University of Technology, Jinzhou 121001, China; zhangtt235@163.com (T.Z.); 15612709005@163.com (B.W.)
2 Songshan Lake Material Laboratory, Dongguan 523000, China; fuying@sslab.org.cn
* Correspondence: xqkong@lnut.edu.cn

Abstract: In order to investigate the effect of high-performance polypropylene (HPP) fiber on the impact resistance of recycled aggregate concrete (RAC), the impact resistance of HPP fiber-reinforced RAC (HFRAC) was investigated using drop-weight impact equipment and compared with steel fiber-reinforced recycled aggregate concrete (SFRAC). The effects of recycled aggregate replacement rates, fiber content, and fiber type were analyzed. Furthermore, the log-normal distribution and two-parameter Weibull distribution statistical methods were used to fit the probability distribution and predict the failure probability of the initial and final crack impact resistance of HFRAC and SFRAC specimens. The experimental results showed that the impact resistance of RAC decreased with the increase in recycled aggregate replacement rates. HPP fiber had little effect on the impact resistance of initial cracking in RAC, but significantly improved the impact resistance of final cracking in RAC, while steel fiber significantly improved the impact resistance of initial cracking in RAC, but had little effect on the impact resistance of final cracking in RAC. The anti-impact energy consumption and ductility of RAC increased with the increase in HPP content. When the HPP fiber content was 1.25% and the recycled aggregate replacement rate was 50%, the maximum impact energy consumption of RAC was 114.5 times higher than that of the plain RAC concrete specimen, and the maximum ductility ratio of the RAC matrix was 118.3. The addition of HPP fibers significantly improved the impact resistance of RAC. The fitting results showed that the distribution characteristics of HFRAC and SFRAC impact resistance were represented by a log-normal distribution and two-parameter Weibull distribution, with the former presenting a better fit to predict the impact resistance of HFRAC and SFRAC.

Keywords: HPP fiber; recycled aggregate concrete; drop-weight test; impact resistance; log-normal distribution; Weibull distribution

1. Introduction

According to incomplete statistics, China produced more than two billion tons of construction waste in 2020. The recycling rate of construction waste was less than 10% [1]. Waste concrete can be processed into recycled aggregate and applied to practical projects. It is beneficial and necessary for the environmental protection and rational and effective utilization of building resources. There is more residual mortar on the surface of reclaimed aggregate. The porosity and water absorption indices of reclaimed aggregate are higher than those of natural aggregate, and the elastic modulus is lower than that of natural aggregate [2]. Direct configuration of recycled aggregate into recycled aggregate concrete (RAC) results in lower compressive strength and elastic modulus. The bending resistance and durability of RAC also deteriorate [3–6]. These limitations limit the use of RAC.

In recent years, it has been reported in domestic and international studies that adding fiber can improve the physical, mechanical, and durability of concrete matrix [7–10]. Among them, steel fiber and polypropylene fiber have been widely used. Steel fiber (SF) is heavy,
easy to rust, and causes concrete spalling, affecting the durability of the structure. Due to its light weight, corrosion resistance, high tensile strength, and excellent strengthening and toughening characteristics, high-performance polypropylene fiber (HPP) has been increasingly applied in concrete [11–15]. Ding et al. [13] found that HPP fiber significantly improved the flexural strength and flexural toughness of HPC with different aspect ratios. HPP fiber with a larger aspect ratio and more roots per unit mass had a better toughening effect. Kiachehr et al. [16] compared the application of HPP fiber and steel fiber in the concrete lining of a tunnel with water; the results showed that the influence of HPP fiber on the flexural toughness and chloride ion penetration resistance of concrete was higher than that of steel fiber. The influence of HPP fiber on the bending toughness of concrete was investigated by Zhu et al. [17]. It was found that HPP fiber had little effect on the initial fracture strength of concrete, but could obviously improve the fracture energy of concrete. Its effect was better than that of steel fiber with the same volume dosage. The effect of HPP fiber on the mechanical properties of concrete after freezing–thawing cycles was studied by Rikabi et al. [18]. The results showed that the thermal expansion coefficient and dynamic elastic modulus of HPP fiber concrete increased and decreased, respectively. The resistance to freezing–thawing cycles was significantly improved.

It can be seen from the above analysis that the bending strength and toughness of concrete can be significantly improved by adding HPP fiber. The current research on HPP fiber is mainly focused on the improvement of mechanical properties of ordinary concrete. The improvement of mechanical properties of RAC by HPP is less studied [19]. In particular, the impact resistance is rarely reported. In order to investigate the effect of HPP fiber on the impact resistance of RAC, 19 groups of RAC specimens with different aggregate replacement rates, fiber types, and dosage were designed and manufactured in this paper. Cube compressive strength and drop-hammer impact tests were carried out to analyze the effects of HPP fiber on the mechanical properties and impact resistance of RAC. The log-normal distribution and Weibull distribution functions were used to fit the impact test results and predict the failure probability, in order to provide a reference for later studies on the engineering design of RAC.

2. Experimental Procedure
2.1. Materials and Mixture Ratio of Concrete

In this study, 42.5R ordinary Portland cement (Bohai brand) was used. The fine aggregate was natural river sand, with a fineness modulus of 2.46. Natural coarse aggregate was used in the test with a particle size of 5–20 mm, apparent density of 2560 kg·m\(^{-3}\), and the bulk density of 1461 kg·m\(^{-3}\). The reclaimed coarse aggregate was crushed by a jaw crusher with a strength grade of C30–C60 waste concrete, and then screened and cleaned. The recycled aggregate was obtained with a particle size of 5–20 mm, apparent density of 2500 kg·m\(^{-3}\), bulk density of 1290 kg·m\(^{-3}\), crushing index of 14.1%, and mud content of 0.85%. The water-reducing rate of PC polyhydroxy acid high-efficiency water-reducing agent was more than 20%. Ordinary tap water was used as mixing water. The physical properties of HPP fiber and steel fiber are shown in Table 1. Their appearance is shown in Figure 1.

| Fiber Type   | Length (mm) | Diameter (mm) | Aspect Ratio | Density (kg·m\(^{-3}\)) | Tensile Strength (MPa) | Elastic Modulus (GPa) | Shape     |
|--------------|-------------|---------------|--------------|--------------------------|------------------------|-----------------------|-----------|
| HPP fiber    | 48          | 0.62          | 77.42        | 960                      | 600                    | 7–10                  | Indentation |
| Steel fiber  | 30          | 1.29          | 23.26        | 7800                     | 590                    | 201                   | Corrugated |

Table 1. Physical properties of fiber.
In order to study the influence of different replacement rates of recycled aggregate, fiber type, and dosage on the impact resistance of RAC, a total of 19 groups of specimens were designed. Four different types of RAC were considered, including three regenerated aggregate replacement rates (I = 0%, I = 50%, I = 100%), two types of fibers (HPP, SF), and four fiber volume fractions (0.5%, 0.75%, 1.0%, 1.25%). Concrete mix ratios are shown in Table 2.

Table 2. RAC proportions of fibers.

| Number | Notation | Cement (kg m⁻³) | Sand (kg m⁻³) | Water (kg m⁻³) | Coarse Aggregates (kg m⁻³) | Water Reducer (kg m⁻³) | Fiber Content (%) |
|--------|----------|----------------|--------------|----------------|---------------------------|-----------------------|------------------|
|        |          |                |              |                | Nature | Recycled |                | HPP | SF |
| C1     | RAC-0-0  | 410            | 719          | 166            | 1072   |          | 2.1            | 0   |    |
| C2     | HFRAC-0-0.5 | 410          | 719          | 166            | 1072   | 2.1      | 0.5%           |     |    |
| C3     | HFRAC-0-0.75 | 410          | 719          | 166            | 1072   | 2.1      | 0.75%          |     |    |
| C4     | HFRAC-0-1.0  | 410          | 719          | 166            | 1072   | 2.1      | 1.0%           |     |    |
| C5     | HFRAC-0-1.25 | 410          | 719          | 166            | 1072   | 2.1      | 1.25%          |     |    |
| C6     | RAC-50-0 | 410            | 719          | 166            | 536    | 536      | 2.1            | 0   |    |
| C7     | HFRAC-50-0.5 | 410          | 719          | 166            | 536    | 536      | 2.1            | 0.5%|    |
| C8     | HFRAC-50-0.75 | 410          | 719          | 166            | 536    | 536      | 2.1            | 0.75%|    |
| C9     | HFRAC-50-1.0 | 410           | 719          | 166            | 536    | 536      | 2.1            | 1.0%|    |
| C10    | HFRAC-50-1.25 | 410          | 719          | 166            | 536    | 536      | 2.1            | 1.25%|    |
| C11    | RAC-100-0 | 410            | 719          | 166            | 1072   |          | 2.1            | 0   |    |
| C12    | HFRAC-100-0.5 | 410          | 719          | 166            | 1072   | 2.1      | 0.5%           |     |    |
| C13    | HFRAC-100-0.75 | 410          | 719          | 166            | 1072   | 2.1      | 0.75%          |     |    |
| C14    | HFRAC-100-1.0 | 410           | 719          | 166            | 1072   | 2.1      | 1.0%           |     |    |
| C15    | HFRAC-100-1.25 | 410          | 719          | 166            | 1072   | 2.1      | 1.25%          |     |    |
| C16    | SFRAC-100-0.5 | 410          | 719          | 166            | 1072   | 2.1      | 0.5%           |     |    |
| C17    | SFRAC-100-0.75 | 410          | 719          | 166            | 1072   | 2.1      | 0.75%          |     |    |
| C18    | SFRAC-100-1.0 | 410           | 719          | 166            | 1072   | 2.1      | 1.0%           |     |    |
| C19    | SFRAC-100-1.25 | 410          | 719          | 166            | 1072   | 2.1      | 1.25%          |     |    |

Notes: In HFRAC-i-j or SFRAC-i-j, HF and SF denote HPP fiber and steel fiber, respectively, i represents the replacement rate of recycle aggregate, and j represents the volume of fiber.

2.2. Sample Preparation and Maintenance

All specimens were made using the forced mixer pre-dry mixing method. The coarse aggregate, sand, and cement were weighed and placed into the mixer for 2 h of dry mixing. Then, the fiber was added. In order for the fibers to be evenly dispersed, they were added into the blender slowly, using a manual process. Finally, the water-reducing agent and
water were added. When the mixture was fully and evenly stirred, the samples were discharged and molded, and then placed on the vibration table for compaction and leveling. After standing at room temperature for 24 h, the specimens were molded. The specimens were placed in a curing room with a temperature of 20 ± 3 °C and relative humidity of more than 90% for 28 days of curing.

2.3. Experimental Methods

2.3.1. Compressive Strength Test

According to the “Standard for mechanical properties test of ordinary concrete” (GB/T50081-2002) [20], standard cube specimens were molded with dimensions of 150 mm × 150 mm × 150 mm, with three pieces in each group. The compressive strength test was carried out using a YAW-5000J computer-controlled electrohydraulic servo compression and shear testing machine.

2.3.2. Impact Resistance Test

According to the “Measurement of properties of fiber reinforced concrete” (suggested by ACI544.2 R-89) [21] and “Standard test methods for fiber reinforced concrete” (CECS 13-2009) [22], the drop-hammer impact device (as shown in Figure 2) designed by our research group was used for the impact resistance test. The sizes of the specimens were 300 mm × 300 mm × 50 mm square plates, with six pieces in each group. The four sides of the specimens were simply supported and installed on the test device. During the test, a steel hammer with a mass of 3 kg and an impact height of 457 mm was used to repeatedly impact the specimen. The bottom surface of the specimen was carefully observed after each impact. When the first visible crack appeared on the bottom surface of the specimen, the impact time was recorded as the initial crack anti-impact time $N_1$. When the crack of the specimen developed upward from the bottom and penetrated the upper surface of the specimen, it was regarded as the final crack failure. This time was recorded as the final crack resistance impact time $N_2$.

Figure 2. Test device of drop-weight impact resistance: (a) design diagram; (b) physical diagram.

3. Results and Discussion

3.1. Compressive Strength

The compressive strength test results of cubes are shown in Table 3. It can be seen that the compressive strength of RAC decreased with the increase in the replacement rate of reclaimed aggregate. For RAC (RAC-i-0), the compressive strength of the specimen decreased by 12.6% when the replacement rate of reclaimed aggregate increased from 0%
to 100%. However, with the increase in HPP fiber content, the compressive strength of HPP fiber-reinforced RAC (HFRAC) specimens did not increase or decrease significantly. This is similar to the conclusion of compressive tests using HPP fiber ordinary concrete [13,23]. The reason is that the elastic modulus of the polypropylene fiber is lower than that of the concrete matrix. The deformation of the fiber is greater than that of the concrete matrix when subjected to external force. Before the concrete matrix cracks, the fiber can hardly limit the deformation of the base material [24]. In addition, it was found that the compressive strength of SF fiber RAC (SFRAC) specimens increased with the increase in steel fiber content. When the steel fiber content was 1.25%, the compressive strength of SFRAC-100-1.25 was increased by 19.6% and 13.2% compared with RAC-100 and HFRAC-100-1.25, respectively. This indicates that the effect of steel fiber on RAC compressive strength was better than that of HPP fiber.

Table 3. Results of compressive strength and impact resistance.

| Number | Notation | fcu (MPa) | Specimen Number | Average Value | W_i/W_f | \( \beta \) |
|--------|----------|----------|----------------|--------------|---------|------|
|        |          |          | N_1/N_2 | N_2/N_2 | N_f/N_2 | N_f/N_2 | N_f/N_2 |
| C1     | RAC-0-0  | 50.1     | 5/6    | 5/5 | 4/6 | 5/7 | 5/5 | 3/3 | 4.5/5.3 | 60.5/71.7 | 0.18 |
| C2     | HFRAC-0-0.5 | 49.3   | 4/33   | 3/26 | 3/18 | 3/16 | 3/11 | \  | 3.2/20.8 | 43.0/279.5 | 5.50 |
| C3     | HFRAC-0-0.75 | 48.5   | 3/51   | 3/142 | 7/220 | 5/256 | 6/243 | 2/132 | 4.3/174.0 | 58.2/2337.839.47 | 36.0 |
| C4     | HFRAC-0-1.0 | 52.1   | 5/178 | 5/380 | 3/73 | 3/390 | 5/130 | \  | 4.2/230.2 | 56.4/3092.935.81 | 14.0 |
| C5     | HFRAC-0-1.25 | 50.0   | 4/368 | 5/652 | 7/616 | 4/397 | 4/361 | 5/412 | 4.8/467.7 | 64.5/6274.596.44 | 14.0 |
| C6     | RAC-50-0 | 47.9     | 4/5   | 3/3   | 5/5 | 2/2 | 4/4 | 4/6 | 3.6/4.1 | 49.3/56.0 | 0.14 |
| C7     | HFRAC-50-0.5 | 48.3   | 3/60   | 3/18 | 3/14 | 3/30 | 3/18 | 3/32 | 3.0/28.6 | 40.3/384.3 | 8.33 |
| C8     | HFRAC-50-0.75 | 46.4   | 5/174 | 3/105 | 3/103 | 3/285 | 3/48 | 3/315 | 3.3/141.6 | 44.8/1903.441.91 | 36.0 |
| C9     | HFRAC-50-1.0 | 47.8   | 5/332 | 3/153 | 3/140 | 3/385 | 6/200 | 4/154 | 4.0/242.0 | 53.7/3251.599.50 | 14.0 |
| C10    | HFRAC-50-1.25 | 49.0   | 3/352 | 8/601 | 3/235 | 3/650 | 3/475 | 3/551 | 4.0/477.3 | 53.7/6412.9118.3 | 14.0 |
| C11    | RAC-100-0 | 44.5     | 1/2   | 4/5   | 3/4 | 2/2 | 3/3 | 5/6 | 3.0/3.7 | 40.3/49.7 | 0.23 |
| C12    | HFRAC-100-0.5 | 45.8   | 3/42 | 2/19 | 2/26 | 5/20 | 3/28 | 2/21 | 2.8/26.0 | 38.1/349.3 | 8.29 |
| C13    | HFRAC-100-0.75 | 46.0   | 3/135 | 2/85 | 3/196 | 3/268 | 3/110 | 4/159 | 3.0/158.8 | 40.3/2134.151.94 | 36.0 |
| C14    | HFRAC-100-1.0 | 46.7   | 2/196 | 3/100 | 6/192 | 3/187 | 4/365 | 3/351 | 3.5/231.8 | 47.0/3114.465.23 | 36.0 |
| C15    | HFRAC-100-1.25 | 46.2   | 3/634 | 8/342 | 4/329 | 4/431 | 4/359 | 3/157 | 4.6/410.2 | 61.8/5535.588.57 | 36.0 |
| C16    | SFRAC-100-0.5 | 48.2   | 2/7   | 4/8   | 3/8 | 3/6 | 3/51 | 4/12 | 4.8/12.3 | 64.9/1657.155.57 | 36.0 |
| C17    | SFRAC-100-0.75 | 49.5   | 8/18 | 3/13 | 4/11 | 5/11 | 5/9 | 4/12 | 4.8/12.3 | 64.9/1657.155.57 | 36.0 |
| C18    | SFRAC-100-1.0 | 52.3   | 7/17 | 6/15 | 5/16 | 6/16 | 7/20 | 5/13 | 6.0/16.2 | 80.6/217.2 | 1.69 |
| C19    | SFRAC-100-1.25 | 53.2   | 5/15 | 17/26 | 10/22 | 7/20 | 13/22 | 10/50 | 10.3/25.8 | 138.8/347.1 | 1.50 |

3.2. Impact Resistance

The results of the free-fall impact resistance tests of the 19 groups of specimens are shown in Table 3. Impact energy dissipation \( W_i \) is the impact resistance performance index. \( \beta \) is the ductility coefficient of the specimens [25,26]. \( W_i \) and \( \beta \) are calculated using Equations (1) and (2), respectively. The comparisons of the impact resistance and ductility of each specimen are shown in Figures 3 and 4, respectively.

\[
W_i = mgh \cdot N_i, \quad (1)
\]

\[
\beta = \frac{N_2 - N_1}{N_1}, \quad (2)
\]

where \( N_i \) is the number of impacts. As can be seen from Table 3, the impact resistance times of RAC-0, RAC-50, and RAC-100 specimens in initial and final cracking were very close, showing obvious brittleness characteristics. The impact resistance of RAC decreased with the increase in the replacement rate of recycled aggregate. The anti-impact energy dissipation of RAC-0 was 1.3 times and 1.4 times that of RAC-50 and RAC-100. The addition of HPP fiber did not significantly improve the initial crack impact resistance of HFRAC specimen, as shown in Figure 3a. The final crack impact resistance of HFRAC specimen
was improved significantly upon adding HPP fiber. The final crack impact resistance of HFRAC specimen increased with the increase in HPP fiber content, as shown in Figure 3b. When the amount of HPP fiber was 1.25%, the final crack anti-impact energy consumption of HFRAC-0-1.25, HFRAC-50-1.25, and HFRAC-100-1.25 was 87.5, 114.5 and 111.4 times that of HPP-free concrete RAC-0, HFRAC-50, and HFRAC-100, respectively. This indicates that HPP fiber played a more significant role in improving the impact resistance of concrete after cracking. This manifestation can be explained as follows: after the cracking of concrete matrix, the stress is transferred to the HPP fiber across the crack. Because of the high tensile strength of HPP fiber, the expansion of crack is inhibited by HPP fiber. Concrete impact failure is delayed. When HPP fibers slip, break, or pull out in matrix, substantial impact energy is absorbed. In addition, the fibers can produce a spring-like cushioning effect during impact loading. Part of the impact energy is converted into elastic potential energy of the fiber [25,27]. The impact kinetic energy is dissipated, and fracture propagation is delayed, improving the impact resistance of RAC.

![Figure 3. Test results of impact resistance: (a) number of blows for first crack $N_1$; (b) number of blows for ultimate crack $N_2$.](image)

![Figure 4. Ductility ratio of HFRAC/SFRAC.](image)
From Figures 3a and 4, we can see that, compared with HPP fiber, SF had a more significant effect on improving the initial crack anti-impact energy consumption of RAC. It can be seen from Figures 3b and 4 that HPP fiber had a more significant effect on improving the final crack anti-impact energy consumption of RAC and toughening RAC than steel fiber. When the HPP fiber content and the replacement rate of regenerated aggregate were 1.25% and 50%, respectively, the maximum impact energy consumption of RAC was 114.5 times that of the pure RAC concrete specimen. The maximum ductility ratio of the RAC matrix was 118.3.

Figure 5 shows the comparison of final failure modes of HFRAC and SFRAC specimens against impact under the same fiber content. Under impact load, both HFRAC and SFRAC specimens showed “cross” cracks. The cracks on the surface of HFRAC specimens were more numerous and thinner than those on the surface of SFRAC specimens. Compared with SFRAC specimens, HFRAC specimens had a larger area and deeper pit impacted by the drop hammer. HFRAC specimens bore more impact times. It is clear that most HPP fibers with bridge cracks were pulled out. The steel fibers were mostly pulled out as a whole. The HPP fibers had better bonding performance with the concrete matrix. This provides further evidence that HPP fiber had a better impact energy dissipation effect.

![Figure 5](image-url)

**Figure 5.** The comparison of impact failure modes: (a) HFRAC specimen (front/back); (b) SFRAC specimen (front/back).

4. Probability Distribution Fitting Test

As a kind of heterogeneous mixture, concrete has more instability in physical and mechanical properties. In order to explore the probability distribution characteristics of HFRAC impact resistance more scientifically and accurately, HFRAC and SFRAC specimens with 100% replacement rate of recycled aggregate were selected as the research objects in
this paper, and log-normal distribution and two-parameter Weibull distribution functions were used to fit the probability distribution of their impact resistance test results.

4.1. Log-Normal Distribution

Log-normal distribution applies to the situation that the natural logarithm transformation follows a normal distribution. Its application range is wide, including for product life and fatigue strength. Normally, the normality of a log-normal distribution is tested by the normal probability paper test \[28,29\]. Taking the impact times \(N(N > 0)\) of the impact resistance test as a random variable, and the transformation \(G = \ln(N)\) of \(N\) was performed. If \(G\) was subject to a normal distribution, the probability density function would be expressed by Equation (3):

\[
f(\ln N) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(\ln N - \mu)^2}{2\sigma^2} \right].
\]  (3)

In this paper, \(N_i\) represents the number of impact (the number of blows for initial crack impact \(N_1\) and the number of blows for final crack impact \(N_2\)), which is the observed value of the log-normal distribution random variable. The cumulative distribution function (or failure probability) of the log-normal distribution is

\[
F(\ln N_i) = P(\ln N_i) = \Phi\left(\frac{\ln N_i - \mu \ln N}{\sigma \ln N}\right),
\]  (4)

where \(Z = \frac{\ln N_i - \mu}{\sigma}\). Then,

\[
\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{N_i^2}{2}\right) dN_i
\]  (5)

is the standard normal distribution.

Taking the inverse function of both sides of Equation (4), we get

\[
\varphi^{-1}[P(\ln N_i)] = \frac{1}{\sigma \ln N} \ln N_i - \frac{\mu \ln N}{\sigma \ln N},
\]  (6)

Let \(Y = \varphi^{-1}[P(\ln N_i)]\), \(X = \ln N_i\), \(a_1 = \frac{1}{\sigma \ln N}\), \(\beta_1 = \frac{\mu \ln N}{\sigma \ln N}\); then, we get

\[
Y = a_1 X - \beta_1.
\]  (7)

If the observed values of specimen impact times are arranged in order from small to large, the corresponding failure probability \(P = (\ln N_i)\) can be expressed as follows \[29\]:

\[
F(\ln N_i) = P(\ln N_i) = \frac{k}{m + 1},
\]  (8)

where \(k\) represents the order number of observed values after arranging the observations in order \((k = 1, 2, 3...), and m is the number of specimens in each group (m = 6 in this test).

The logarithmic normal distribution linear fitting analysis results of impact times \(N_1\) and \(N_2\) of HFRAC and SFRAC specimens are shown in Figure 6 and Table 4. It can be seen from Table 4 that the minimum value and the maximum value of the fitting correlation coefficient \(R^2\) were 0.853 and 0.998, respectively. A linear correlation is considered when the fitting correlation coefficient \(R^2\) is greater than 0.7 \[30\]. As shown in Figure 6, it can be seen that the fitting curve of the test results was approximately a straight line. It can be seen that \(\ln N_i\) and \(\varphi^{-1}[P(\ln N_i)]\) had a good linear relationship. The distribution characteristics of shock resistance times of HFRAC and SFRAC followed a log-normal distribution.
Figure 6. Linear regression of $N_1$ and $N_2$ in log-normal distribution for FRAC.

Table 4. Linear fitting results of log-normal distribution.

| Number | Notation       | $N_1$      | $N_2$      |
|--------|----------------|------------|------------|
|        |                | $\alpha_1$ | $\beta_1$  | $R^2$      | $\alpha_1$ | $\beta_1$  | $R^2$      |
| C11    | RAC-100-0      | 1.295      | 1.271      | 0.918      | 1.590      | 1.910      | 0.982      |
| C12    | HFRAC-100-0.5  | 1.857      | 1.803      | 0.972      | 2.445      | 7.868      | 0.853      |
| C13    | HFRAC-100-0.75 | 2.998      | 3.238      | 0.976      | 1.886      | 9.426      | 0.997      |
| C14    | HFRAC-100-1.0  | 2.019      | 2.511      | 0.988      | 1.146      | 6.259      | 0.888      |
| C15    | HFRAC-100-1.25 | 1.862      | 2.617      | 0.868      | 1.470      | 8.712      | 0.881      |
| C16    | SFRAC-100-0.5  | 1.998      | 2.181      | 0.998      | 3.600      | 7.434      | 0.955      |
| C17    | SFRAC-100-0.75 | 2.246      | 3.436      | 0.949      | 3.178      | 7.906      | 0.897      |
| C18    | SFRAC-100-1.0  | 4.642      | 8.278      | 0.966      | 5.178      | 14.360     | 0.937      |
| C19    | SFRAC-100-1.25 | 1.765      | 3.986      | 0.991      | 1.752      | 5.554      | 0.894      |

4.2. Two-Parameter Weibull Distribution

Weibull probability distribution has the advantages of wide adaptability and undemanding sample size. It is widely used in fatigue damage, impact performance, and other research fields [31,32]. Taking the shock resistance number $N (N > 0)$ as the random variable, the two-parameter Weibull distribution test was carried out. The probability density function of the two-parameter Weibull distribution can be expressed as follows:

$$f(N) = \frac{b}{N_0} \left( \frac{N}{N_0} \right)^{b-1} \exp \left[ -\left( \frac{N}{N_0} \right)^b \right],$$  \hspace{1cm} (9)$$

where $N_0$ is the characteristic life parameter (or scale parameter), and $b$ is the shape parameter of the Weibull distribution.

$N_i$ was the observed value of the random variable in the two-parameter Weibull distribution. The cumulative distribution function (or failure probability) of the two-
parameter Weibull distribution is expressed by Equation (10). The reliability probability of impact times is expressed by Equation (11) for impact times greater than \( N_i \).

\[
F(N_i) = P(N_i) = 1 - \exp\left[-\left(\frac{N_i}{N_a}\right)^b\right]. \tag{10}
\]

\[
P_c(N_i) = 1 - P(N_i) = \exp\left[-\left(\frac{N_i}{N_a}\right)^b\right]. \tag{11}
\]

Taking the equivalent transformation of Equation (11) and the two logarithms, we get

\[
\ln \ln \left(\frac{1}{P_c(N_i)}\right) = b \ln N_i - b \ln N_a. \tag{12}
\]

With \( Y = \ln \ln \left(\frac{1}{P_c(N_i)}\right) \), \( X = \ln N_i \), \( a_2 = b \), \( \beta_2 = b \ln N_a \), we get

\[
Y = a_2 X - \beta_2 \tag{13}
\]

If the observed values of specimen impact times are arranged in the order of sequential statistics from small to large, the corresponding survival probability \( P_c(N_i) \) can be expressed as follows [32]:

\[
P_c(N_i) = 1 - \frac{k}{m + 1} \tag{14}
\]

where \( k \) is the order number of observed values after they are arranged in sequence (\( k = 1, 2, 3, \ldots \)), and \( m \) is the number of specimens in each group (\( m = 6 \) in this test).

The two-parameter Weibull distribution linear fitting results of impact times of HFRAC and SFRAC are shown in Table 5 and Figure 7. From Table 5, it can be seen that the minimum value and the maximum value of the fitting correlation coefficient \( R^2 \) were 0.757 and 0.998, respectively. It can be seen that the data points of each specimen were basically distributed on the fitted straight lines (Figure 7), suggesting that \( \ln N_i \) and \( \ln \ln \left(\frac{1}{P_c(N_i)}\right) \) have a good linear relationship. The distribution characteristics of shock resistance times of HFRAC and SFRAC followed a two-parameter Weibull distribution.

| Number | Notation      | \( N_1 \) | \( R^2 \) | \( a_2 \) | \( \beta_2 \) | \( R^2 \) |
|--------|---------------|--------|-------|--------|-------|-------|
| C11    | RAC-100-0     | 1.573  | 0.974 | 1.843  | 2.680 | 0.995 |
| C12    | HFRAC-100-0.5 | 2.027  | 0.940 | 2.769  | 9.380 | 0.757 |
| C13    | HFRAC-100-0.75| 3.628  | 0.998 | 2.213  | 11.530| 0.973 |
| C14    | HFRAC-100-1.0 | 2.382  | 0.975 | 1.328  | 7.718 | 0.837 |
| C15    | HFRAC-100-1.25| 2.076  | 0.774 | 1.781  | 11.027| 0.932 |
| C16    | SFRAC-100-0.5 | 2.296  | 0.994 | 4.215  | 9.163 | 0.896 |
| C17    | SFRAC-100-0.75| 2.602  | 0.895 | 3.650  | 9.546 | 0.837 |
| C18    | SFRAC-100-1.0 | 5.463  | 0.997 | 6.088  | 17.352| 0.916 |
| C19    | SFRAC-100-1.25| 2.099  | 0.996 | 2.001  | 6.808 | 0.809 |
In addition, the correlation coefficient $R^2$ values in Tables 4 and 5 were compared. The degree of distribution characteristics for impact resistance times $N_1$ and $N_2$ of different RAC specimens with respect to the log-normal distribution and Weibull distribution was different. In most specimens, the log-normal distribution $R^2$ value of the distribution characteristics of $N_1$ and $N_2$ was greater than that of the Weibull distribution. When HPP fiber dosage was 0.5 and 1.0, respectively, the $N_1$ and $N_2$ distribution characteristics of HFRAC-100-0.5 and HFRAC-100-1.0 were better described by a log-normal distribution. When 0.5–1.25% steel fiber was added, most log-normal distribution $R^2$ values of SFRAC specimens were greater than those of the Weibull distribution. Therefore, the impact resistance times $N_1$ and $N_2$ of RAC specimens better obeyed the log-normal distribution characteristics in this study.

4.3. $P$–$\ln N_f$ Curve of Impact Resistance

The log-normal distribution could better test the distribution law of impact resistance times of fiber RAC specimens. The anti-impact times ($N_i$) of fiber RAC specimens with different failure probabilities were obtained using Equations (6) and (7).

$$N_i = \exp\left(\frac{\varphi^{-1}(P) + \beta_1}{\alpha_1}\right).$$ (15)

According to Equation (15) and the fitting results of Table 4, the anti-impact times of fiber RAC specimens with given failure probabilities were calculated. The results can be seen in Table 6. On the basis of the results, the relationship curve between final crack resistance time $N_2$ and fiber volume content $V_f$ of RAC specimens in each group were plotted under the given failure probability $P$, i.e., the $P$–$\ln N_2$–$V_f$ curve (Figure 8). Under different failure probabilities, there was a roughly quadratic linear correlation between the impact resistance time ($N_2$) and fiber volume content ($V_f$) of fiber RAC specimens.

Table 6. Impact blows of FRAC for different probabilities of failure.

| Number | Notation          | 5%   | 15%   | 30%   |
|--------|-------------------|------|-------|-------|
|        |                   | $N_1$| $N_2$ | $N_1$| $N_2$| $N_1$| $N_2$|
| C11    | RAC-100-0         | 1    | 1     | 1    | 2    | 2    | 2    |
| C12    | HFRAC-100-0.5     | 1    | 13    | 2    | 16   | 2    | 20   |
| C13    | HFRAC-100-0.75    | 2    | 62    | 2    | 86   | 2    | 112  |
| C14    | HFRAC-100-1.0     | 2    | 56    | 2    | 95   | 3    | 149  |
| C15    | HFRAC-100-1.25    | 2    | 123   | 2    | 186  | 3    | 263  |
| C16    | SFRAC-100-0.5     | 1    | 5     | 2    | 6    | 2    | 7    |
was different. In most specimens, the log-normal distribution $R^2$ value of the distribution characteristics of fiber RAC specimens was greater than that of the Weibull distribution. When HPP fiber content was 0.5–1.25%, the log-normal distribution of HFRAC and SFRAC was better described by a log-normal distribution.

4.3. $P$–$\ln N_2$–$V_f$ Curve of Impact Resistance

The impact resistance of RAC decreased with the increase in the replacement rate of recycled aggregate. The initial crack anti-impact energy consumption of RAC was significantly improved by adding steel fiber. The final crack anti-impact energy consumption of RAC was not significantly affected by steel fibers. The exact opposite result was obtained upon adding HPP fiber, whereby the final crack anti-impact energy consumption of RAC was significantly improved. When the HPP fiber content and the replacement rate of recycled aggregate were 1.25% and 50%, respectively, the maximum impact energy consumption of RAC was 114.5 times that of the plain RAC concrete specimen, and the maximum ductility ratio of the RAC matrix was 118.3.

The log-normal distribution function was more suitable for fitting the shock resistance times of fiber RAC specimens using mathematical statistical functions. The results of the study were as follows:

1. The compressive strength of RAC decreased with the increase in replacement rate of recycled aggregate. The compressive strength of RAC increased with the increase in steel fiber content. The compressive strength of RAC was not significantly affected by HPP fiber content. When the steel fiber content was 1.25%, the compressive strength of SFRAC-100-1.25 was increased by 19.6% and 13.2% compared with RAC-100 and HFRAC-100-1.25, respectively.

2. The impact resistance of RAC decreased with the increase in the replacement rate of recycled aggregate. The initial crack anti-impact energy consumption of RAC was significantly improved by adding steel fiber. The final crack anti-impact energy consumption of RAC was not significantly affected by steel fibers. The exact opposite result was obtained upon adding HPP fiber, whereby the final crack anti-impact energy consumption of RAC was significantly improved. When the HPP fiber content and the replacement rate of recycled aggregate were 1.25% and 50%, respectively, the maximum impact energy consumption of RAC was 114.5 times that of the plain RAC concrete specimen, and the maximum ductility ratio of the RAC matrix was 118.3.

3. The log-normal distribution and two-parameter Weibull distribution function were used to fit the impact test results of HFRAC and SFRAC. The test results were in good compliance with the log-normal distribution and two-parameter Weibull distribution. The log-normal distribution function was more suitable for fitting the shock resistance times of HFRAC and SFRAC distribution characteristics. Under different failure probabilities, there was a roughly quadratic linear correlation between the final crack anti-impact energy consumption of RAC and the steel fiber content. The compressive strength of RAC increased with the increase in the aggregate substitution rates, fiber contents, and fiber types on RAC impact resistance were analyzed. The log-normal distribution and the two-parameter Weibull distribution were used to perform fitting analysis and failure probability prediction on the impact test results of fiber RAC specimens using mathematical statistical functions. The results of the study were as follows:

| Number | Notation          | Failure Probability $P$ |
|--------|-------------------|------------------------|
|        |                   | 5% $N_1$  | 15% $N_2$ | 30% $N_1$ | 30% $N_2$ |
| C17    | SFRAC-100-0.75    | 2         | 7         | 3         | 9         |
| C18    | SFRAC-100-1.0     | 4         | 12        | 5         | 13        |
| C19    | SFRAC-100-1.25    | 4         | 9         | 5         | 13        |

Figure 8. $P$–$\ln N_2$–$V_f$ curves: (a) HFRAC curves in log-normal distribution; (b) SFRAC curves in log-normal distribution.

5. Conclusions

The effect of HPP fiber on the impact resistance of RAC was investigated in this research. The impact resistances of HFRAC were determined using drop-weight impact equipment, with SFRAC as the reference specimen. The effects of different regenerates aggregate substitution rates, fiber contents, and fiber types on RAC impact resistance were analyzed. The log-normal distribution and the two-parameter Weibull distribution were used to perform fitting analysis and failure probability prediction on the impact test results of fiber RAC specimens using mathematical statistical functions. The results of the study were as follows:

1. The compressive strength of RAC decreased with the increase in replacement rate of recycled aggregate. The compressive strength of RAC increased with the increase in steel fiber content. The compressive strength of RAC was not significantly affected by HPP fiber content. When the steel fiber content was 1.25%, the compressive strength of SFRAC-100-1.25 was increased by 19.6% and 13.2% compared with RAC-100 and HFRAC-100-1.25, respectively.

2. The impact resistance of RAC decreased with the increase in the replacement rate of recycled aggregate. The initial crack anti-impact energy consumption of RAC was significantly improved by adding steel fiber. The final crack anti-impact energy consumption of RAC was not significantly affected by steel fibers. The exact opposite result was obtained upon adding HPP fiber, whereby the final crack anti-impact energy consumption of RAC was significantly improved. When the HPP fiber content and the replacement rate of recycled aggregate were 1.25% and 50%, respectively, the maximum impact energy consumption of RAC was 114.5 times that of the plain RAC concrete specimen, and the maximum ductility ratio of the RAC matrix was 118.3.

3. The log-normal distribution and two-parameter Weibull distribution function were used to fit the impact test results of HFRAC and SFRAC. The test results were in good compliance with the log-normal distribution and two-parameter Weibull distribution. The log-normal distribution function was more suitable for fitting the shock resistance times of HFRAC and SFRAC distribution characteristics. Under different failure prob-
abilities, the final crack resistance times of HFRAC and SFRAC specimens exhibited a quadratic linear relationship to their fiber volume content.

**Author Contributions:** Conceptualization, X.K.; methodology, X.K.; software, T.Z. and B.W.; validation, T.Z.; formal analysis, Y.F.; investigation, T.Z.; resources, Y.F.; data curation, T.Z.; writing—original draft preparation, T.Z.; writing—review and editing, T.Z. and X.K.; visualization, Y.F.; supervision, X.K.; project administration, X.K.; funding acquisition, Y.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Nature Science Foundation of China (51704029), LiaoNing Revitalization Talents Program (XLYC1807044, XLYC1807050) and Superior College Science Technology Research Project of Liaoning Province (LJKZ0622).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

**References**

1. Xu, G.; Shen, W.; Zhang, B.; Li, Y.; Ji, X.; Ye, Y. Properties of recycled aggregate concrete prepared with scattering-filling coarse aggregate process. *Cem. Concr. Compos.* 2018, 93, 19–29. [CrossRef]

2. Luo, S.R.; Zheng, X.; Huang, H.S. Experimental study on pretreatment of creep behavior of recycled coarse aggregate and creep behavior of recycled aggregate concrete. *J. Build. Mater.* 2016, 19, 242–247.

3. Wang, Y.; Hughes, P.; Niu, H.; Fan, Y. A new method to improve the properties of recycled aggregate concrete: Composite addition of basalt fiber and nano-silica. *J. Clean. Prod.* 2019, 236, 117602. [CrossRef]

4. Zou, C.H.; Chen, Z.P. Mechanical properties of recycled concrete made with different types of coarse aggregate. * Constr. Build. Mater.* 2017, 134, 497–506. [CrossRef]

5. Mohammed, S.I.; Najim, K.B. Mechanical strength, flexural behavior and fracture energy of Recycled Concrete Aggregate self-compacting concrete. *Structures* 2019, 23, 34–43. [CrossRef]

6. Debieb, F.; Courard, L.; Kenai, S.; Degeimbre, R. Mechanical and durability properties of concrete using contaminated recycled aggregates. *Cem. Concr. Compos.* 2010, 32, 421–426. [CrossRef]

7. Mudadu, A.; Tiberti, G.; Germano, F.; Plizzari, G.A.; Morbi, A. The effect of fiber orientation on the post-cracking behavior of steel fiber reinforced concrete under bending and uniaxial tensile tests. *Cem. Concr. Compos.* 2018, 93, 274–288. [CrossRef]

8. Teng, S.; Afroughsabet, V.; Ostertag, C.P. Flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete. * Constr. Build. Mater.* 2018, 182, 504–515. [CrossRef]

9. Yu, J.C.; Zhao, Q.X. Effect of steel fiber on creep behavior of concrete. *J. Chin. Ceram. Soc.* 2013, 41, 1087–1093.

10. Das, C.S.; Dey, T.; Dandapat, R.; Mukharjee, B.B.; Kumar, J. Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete. * Constr. Build. Mater.* 2018, 189, 649–659. [CrossRef]

11. Yin, S.; Chen, F.B.; Min, R.; Dandapat, R. High strength macro synthetic fibre concrete international projects project cases. *China Concr. Cem. Prod.* 2018, 6, 51–55.

12. Li, D.; Liu, S. Macro polypropylene fiber influences on crack geometry and water permeability of concrete. * Constr. Build. Mater.* 2020, 231, 117128. [CrossRef]

13. Ding, Y.N.; Cao, J.F. Experiment study of behaviour of modified macro-polypropylene fiber reinforced high performance concrete. *J. Dalian Univ. Technol.* 2007, 47, 707–711.

14. Kazmi, S.M.S.; Munir, M.J.; Wu, Y.-F.; Patnaikuni, I. Effect of macro-synthetic fibers on the fracture energy and mechanical behavior of recycled aggregate concrete. * Constr. Build. Mater.* 2018, 189, 857–868. [CrossRef]

15. Deng, Z.; Li, J. Mechanical behaviors of concrete combined with steel and synthetic macro-fibers. *Int. J. Phys. Sci.* 2006, 1, 57–66. [CrossRef]

16. Behfarinia, K.; Behravan, A. Application of high performance polypropylene fibers in concrete lining of water tunnels. *Mater. Des.* 2014, 55, 274–279. [CrossRef]

17. Zhu, H.B.; Wu, K.F.; Li, J.S.; Roesler, J.R. Effect of synthetic fibers on mechanical proportion of fiber reinforced concrete. *J. Tongji Univ. Nat. Sci. Ed.* 2016, 44, 1894–1901.

18. Al Rikabi, F.T.; Sargand, S.M.; Khoury, I.; Roesler, J.R. Material properties of synthetic fiber-reinforced concrete under freeze-thaw conditions. *J. Mater. Civ. Eng.* 2018, 30, 04018090. [CrossRef]

19. Kazmi, S.M.S.; Munir, M.J.; Wu, Y.-F.; Patnaikuni, I.; Zhou, Y.; Xing, F. Axial stress-strain behavior of macro-synthetic fiber reinforced recycled aggregate concrete. *Cem. Concr. Compos.* 2019, 97, 341–356. [CrossRef]

20. GB/T50081–2002; Standard for Mechanical Properties Test of Ordinary Concrete. National Standard of the People’s Republic of China. Architectural Industry Press: Beijing, China, 2003.
21. ACI544.2R-89; Measurement of Properties of Fiber Reinforced Concrete. American Concrete Institute: Detroit, MI, USA, 1999; pp. 6–7.
22. CECS13-2009; Standard Test Methods for Fiber Reinforced Concrete. China Association for Engineering Construction Standardization. China Plans Publishing House: Beijing, China, 2010; p. 114.
23. Hasan, M.J.; Afroz, M.; Mahmud, H.M.I. An experimental investigation on mechanical behavior of macro synthetic fiber reinforced concrete. Int. J. Civ. Environ. Eng. 2013, 17, 18–23.
24. Yao, W.; Ma, Y.P.; Tan, M.H. Effects of polypropylene fibers on the physical and mechanical properties of cement based composites(II)-mechanical properties. Constr. Build. Mater. 2000, 3, 235–239.
25. Kong, X.Q.; He, W.C.; Xing, L.L.; Patnaikuni, I. Effect of steel fiber-polypropylene fiber hybrid addition on impact resistance of recycled aggregate concrete. Acta Mater. Compos. Sin. 2020, 37, 1763–1773.
26. Li, J.J.; Niu, J.G.; Wan, C.J.; Jin, B.; Yin, Y.L. Investigation on mechanical properties and microstructure of high performance polypropylene fiber reinforced lightweight aggregate concrete. Constr. Build. Mater. 2016, 118, 27–35. [CrossRef]
27. Pan, H.M.; Ma, Y.C. Impact resistance of steel fiber reinforced concrete and its mechanism crack resistance and toughening. J. Build. Mater. 2017, 20, 956–961.
28. Zhu, X.C. Study on the Test Method for Impact Resistance of Cement Concrete; Tianjin University: Tianjin, China, 2016.
29. Wang, L.C.; Wang, H.T.; Liu, H.Y. Experimental study and statistical evaluation for impact resistance of steel fiber reinforced lightweight aggregate concrete. J. Dalian Univ. Technol. 2010, 50, 557–563.
30. Rahmani, T.; Kiani, B.; Shekarchizadeh, M.; Safari, A. Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test. Constr. Build. Mater. 2012, 37, 360–369. [CrossRef]
31. Weibull, W. A Statistical Distribution Function of Wide Applicability. J. Appl. Mech. 1951, 18, 293–297. [CrossRef]
32. Chen, X.Y. Experimental Research on Impact Resistance of Fiber Reinforced Concrete; Dalian University of Technology: Dalian, China, 2010.