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Research Article

A Study of the Impact Resistance of Rubber Concrete at Low Temperatures (−30°C)

Gang Xue,[1] Jia-xiang Liu ,[2] and Mei-ling Cao[3]

[1]*Professor, School of Civil Engineering, Inner Mongolia University of Science and Technology, Baotou 014010, China*
[2]*Master, School of Civil Engineering, Inner Mongolia University of Science and Technology, Baotou 014010, China*
[3]*Master, Zhejiang Southeast Space Frame Company Limited, Hangzhou 310000, China*

Correspondence should be addressed to Jia-xiang Liu; liujiaxiangbs@163.com

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In the present study, the impact resistance of rubber concrete at low temperatures (−30°C) was examined. The initial and ultimate crack impact times and the ductility indexes were evaluated. This study's specimens were prepared by adding two different sizes of rubber particles (20 mesh and 50 mesh) in different ratios (0%, 5%, 10%, 15%, and 20%) at both 25°C and −30°C. The concrete specimens were evaluated using a drop hammer weight test method. The results showed that the initial and ultimate crack impact times and ductility indexes of the rubber concrete specimens had decreased at −30°C. Also, the decrease amplitudes were determined to be lower than those of the reference concrete specimens. Consideration was given in this study to the large variations in the impact values, and a two-parameter Weibull distribution method was adopted in order to analyze the obtained experimental data. The results had demonstrated that the impact times of the rubber concrete specimens could be described using the two-parameter Weibull distribution method results.

1. Introduction

With the rapid increases in the number of motor vehicles, the number of used tires has also been increasing [1]. According to the predictions made by LMC Automotive, by 2024, the vehicle fleet will have grown by more than 25% [2], which will subsequently result in higher numbers of used tires. It takes up to a century for used tires to degrade in the environment [3]. Therefore, high numbers of used vehicle tires will undoubtedly cause environmental pollution problems. In the past, the burning of used tires was found to be the easiest and cheapest method of disposal. However, such incineration methods had produced toxic smoke, and it was found that the flames were difficult to extinguish. In addition, the powder residues which remained after tire burning processes resulted in serious soil pollution issues, and the oil generated by melting tires were found to cause pollution in nearby soil and water [4, 5].

In recent years, the construction industry has faced the challenge of integrating sustainable development into production activities. Therefore, it has been necessary to incorporate more environmentally friendly materials into concrete in the form of aggregate additions [6]. These attempts have not only helped dealing with the problems presented in the disposal of large numbers of used tires but also improved some of the poorer properties of concrete [7, 8]. Therefore, with these goals in mind, some researchers have used the tire waste particles in concrete and studied the subsequent effects on the physical and mechanical properties of experimental concrete specimens [9–11]. For example, many studies have shown that adding rubber to concrete can reduce its compressive strength [12], tensile strength [13], and modulus of elasticity [14]. However, the addition of rubber can potentially increase the energy absorption [15], wear resistance [16], and frost resistance [17] of concrete. Concrete structures are inevitably subjected to dynamic loads from various machinery or vehicles during their service life, and the impact resistance of concrete can be used to evaluate the dynamic characteristics. Some previous studies have examined the impact resistance of rubber concrete. For example, Topcu and Avcular performed drop-weight impact tests on rubber concrete specimens of

$\phi 150 \times 300$ mm [18]. Zhao et al. used a drop-weight device which had been recommended by ACI-544 to perform drop hammer tests on rubber concrete specimens of $\phi 150 \times 60$ mm [19]. Also, Wang and Li performed drop-weight impact tests for the purpose of examining the potential of lightweight aggregate rubber concrete [20]. The results of the aforementioned studies have shown that adding rubber powder into concrete can improve the impact resistance of the concrete. However, these studies have mainly focused on the role of rubber powder in improving the impact resistance of concrete at room temperature [21]. There have only been a few studies conducted at the current time regarding the impact resistance of rubber concrete at low temperatures. In particular, the effects of low temperatures on the impact life and failure probabilities of rubber concrete have yet to be explored in detail [22, 23].

At the present time, there is no recognized unified impact test method. This research study was referred to the Deng drop-hammer impact test method [24] to study the impact resistance of rubber concrete at −30°C, and a two-parameter Weibull distribution method was adopted to analyze the impact test data [25]. As a result, the impact life of rubber concrete under different failure probability conditions was successfully predicted.

2. Significance

It has been previously found that used rubber waste particles can be effectively utilized in rubber concrete structures. The temperature in some alpine regions often reach −30°C or even lower during the winter seasons. There are currently many airport runways, highway systems, road-bed sleepers, and bridge pier constructions which are often affected by various destructive impact loads. Therefore, it has become necessary to analyze the dynamic mechanical behaviors and failure mechanisms of rubber concrete during the interactions of low temperatures and dynamic loads. However, the current research regarding the impact resistance of rubber concrete has mostly concentrated on room temperature conditions. Research studies of the impact resistance of rubber concrete at low temperatures have practical application values for evaluating pavement engineering designs in the alpine regions.

3. Materials and Methods

3.1. Materials. In this study's experimental process, 42.5 Portland cement was used. The chemical compositions and physical properties of the cement specimens are presented in Tables 1 and 2, respectively. The fine aggregate used in this study was medium sand with particle size less than 5 mm, and the screening results of the fine aggregates are shown in Table 3. The bulk density of the crushing stone was 1,550 kg/m^3 and particle sizes ranged between 5 and 25 mm. The screening results of the coarse aggregates are shown in Table 4. Also, the fly ash was Grade II, and the slag powder was Grade S95. The water reducer was a polycarboxylic acid superplasticizer, and the water-reducing ratio was 25%.

The rubber powder used in the current study was 20 mesh and 50 mesh. The technical indicators of the rubber power are detailed in Table 5.

3.2. Mixing and Specimen Preparation. In this study's experiment, an HJW60 concrete mixer was used. First, the coarse aggregates, fine aggregates, and rubber powder were thoroughly mixed in a dry state, in which the rubber powder had replaced part of fine aggregates in the concrete specimens in equal volumes. Then, the cement powder was added and mixed thoroughly. The third step was that the remaining mixing water and superplasticizer were slowly added during the stirring process. The mixed concrete was then poured into oiled molds, and the molds were removed after a 24-hour storage period at room temperature. At this point in the experiment, the specimens were cured for 28 days at a temperature of (20 ± 2)°C and a humidity of 95%.

The rubber concrete was designed based on the standard C30 reference concrete. The reference concrete mix proportion was designed according to the Chinese standard: JGJ 55-2011 [26]. This study's various concrete mixes were prepared using a water-to-binder ratio of 0.4 and slumps between 50 and 100 mm. Fly ash and slag powder were blended into concrete at 50 kg/m^3 and 60 kg/m^3, respectively. Table 6 illustrates the mix proportions used in the current study.

3.3. Test Program. Table 7 shows the elasticity modulus and compressive strengths of this study's rubber concrete specimens measuring $150 \times 150 \times 300$ mm at 25°C and −30°C following a 28-day curing period, respectively, in accordance with the Chinese standard: GB/T 50081-2002 [27].

A total of 144 prismatic specimens measuring $100 \times 100 \times 400$ mm were produced in the current study. There were 8 specimens in each group, for a total of 18 sets of specimens. The specimens which had been selected for the low-temperature tests were placed in an industrial refrigerator for a 72-hour period at −30°C in order to ensure that the specimens were fully uniform in temperature. Those specimens were then immediately taken out for the purpose of performing this study's experimental tests. Since the duration of the testing process was less than 10 minutes, the temperature changes in the specimens during that period were very small, and it was considered that those minimal changes would have little impact on the test results [28]. The drop-weight impact test were performed on specimens measuring $100 \times 100 \times 400$ mm under both 25°C and −30°C temperature conditions. The hammer was constructed of a solid steel ball weighing 1.5 kg, and the free drop height was 300 mm. The frequency of the repeated impacts was maintained at 5 s/time. The schematic of the experimental setup is detailed in Figure 1.

3.4. Test Procedure. This study's impact test procedures are as follows:

(1) The specimens were installed in a self-made free fall hammer impact device. One side of each specimen was delegated as the load-bearing side. Then, a steel

Table 1: Chemical compositions of the cement specimens.

Chemical composition	MgO	Fe_2O_3	Al_2O_3	SiO_2	SO_3	K_2O	Na_2O_2	CaO	Insolubles	Ignition loss
Content (%)	2.64	3.12	4.18	20.23	2.78	0.64	0.13	64.07	0.71	1.50

Table 2: Physical properties of the cement specimens.

Water requirement for normal consistency (%)	Density (g/cm^3)	Fineness (%)	Stability (boiling method)	Setting time (min)	
				Initial	Final
28	3.1	3.0	Qualification	125	220

Table 3: Screening results of the fine aggregates.

Square sieve aperture (mm)	Sieve balance (%)	Cumulative sieve balance (%)
4.75	2.8	2.8
2.30	6.7	9.5
1.18	13.4	22.9
0.6	30.3	53.4
0.3	37.4	90.8

Table 4: Screening results of the coarse aggregates.

Square sieve aperture (mm)	Sieve balance (%)	Cumulative sieve balance (%)
26.5	0.0	0.0
19	17.7	17.7
16	34.9	52.6
9.5	33.9	86.5
4.75	13.0	99.5
<4.75	0.5	100

Table 5: Technical indicators of the rubber powder.

Rubber powder (mesh)	Average particle size (μm)	Screen size (μm)	Sieving rate (%)	Ash content (%)	Acetone extractive (%)	Tensile strength (MPa)	Elongation at break (%)
20	765	850	≥95	≤8	≤8	≥15	≥500
50	258	300	≥90	≤8	≤8	≥15	≥500

Table 6: Proportions of the rubber concrete mixes.

Specimen number	Cement (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	Rubber powder (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)
NC-0.40	290	50	60	0	770	1085	160
RC-20-5	290	50	60	26.7	731.5	1085	160
RC-20-10	290	50	60	53.5	693.1	1085	160
RC-20-15	290	50	60	80.2	654.5	1085	160
RC-20-20	290	50	60	106.9	615.9	1085	160
RC-50-5	290	50	60	26.7	731.5	1085	160
RC-50-10	290	50	60	53.5	693.1	1085	160
RC-50-15	290	50	60	80.2	654.5	1085	160
RC-50-20	290	50	60	106.9	615.9	1085	160

NC-0.40 shows that the water-binder ratio is 0.40 and rubber content is 0% of reference concrete; RC-20-5 shows that rubber powder is 20 mesh and rubber content is 5% of rubber concrete. Other specimens are expressed in a similar way.

pad measuring $100 \times 100 \times 8$ mm was placed in the middle of the top surface of the specimen for the purpose of preventing excessive concentrations under the impact loading conditions.

(2) A strain gauge was placed in the middle of the bottoms of each specimen. Then, the strain gauges were connected to a DH3820 dynamic strain gauge. The data were then automatically collected via a

Table 7: Elastic modulus and compressive strengths of the rubber concrete specimens at 25°C and −30°C.

Number	Elastic modulus (GPa)	Compressive strength (MPa)
25°C		
NC-0.40	29.09	42.46
RC-20-5	27.84	35.35
RC-20-10	24.68	26.05
RC-20-15	19.73	21.34
RC-20-20	16.86	17.89
RC-50-5	24.56	31.37
RC-50-10	22.96	25.75
RC-50-15	18.35	19.11
RC-50-20	17.31	15.63
−30°C		
NC-0.40	31.39	50.27
RC-20-5	30.84	43.61
RC-20-10	30.18	40.46
RC-20-15	26.73	34.99
RC-20-20	24.86	26.92
RC-50-5	30.04	42.24
RC-50-10	28.37	38.82
RC-50-15	26.85	33.59
RC-50-20	23.42	23.63

1: sleeve
2: impact hammer
3: steel pad
4: clamp
5: counter

Figure 1: Impact test device.

computer terminal. When the first microcracks were produced in the specimens, the strain values at the bottom tensile regions of the specimens had abruptly changed, and the initial crack impact times (N_1) were recorded.

(3) Following the crack appearances, the crack propagation patterns of the specimens undergoing repeated impact loading were continuously observed. When the main cracks had penetrated the upper surfaces of the specimens, the ultimate crack impact times (N_2) were recorded.

4. Results and Analysis

4.1. Impact Test Results. In the present study, the impact energy and ductility of the samples were calculated using the following equation [29, 30]:

$$W = N_2 \times mgh,$$
$$\beta = \frac{N_2}{N_1}, \tag{1}$$

where W represents the impact energy (J), N_1 denotes the initial crack impact times, N_2 indicates the ultimate crack impact times, m represents the mass of the impact hammer (1.5 kg), g is the acceleration due to gravity (9.81 m/s^2), h indicates the releasing height of the drop hammer (300 mm), and β is the ductility index.

The impact test results at 25°C and −30°C are presented in Tables 8 and 9. The results of the drop hammer impact tests were carefully analyzed.

As shown in Tables 8 and 9, when compared with the reference concrete at −30°C, the impact resistance of the rubber concrete RC-20-20 had been increased by 346.2%. Also, the impact resistance of the rubber concrete RC-50-20 had been increased by 361.5% when compared with the reference concrete. Furthermore, when compared with the reference concrete at 25°C, the impact resistance of the rubber concrete RC-20-20 was observed to have increased by 275.1% and the impact resistance of the rubber concrete RC-50-20 had increased by 225.1%. This study's comparative analysis results showed that the increased amplitudes of the impact resistance of the rubber concrete specimens were definitely higher than those of the reference concrete at −30°C.

It was observed in this study that, with the decrease in temperature, the pore solutions in the concrete specimens had become frozen. The pores were filled with higher strength ice, which increased the elastic modulus of the rubber concrete [31]. When the rubber concrete specimens were subjected to dynamic loads, it was found that the mixtures of rubber powder and cement stone were able to buffer and absorb the majority of impact energy, which subsequently had effectively eliminated the stress concentrations in the void portions. Therefore, the increased amplitudes of the impact resistance of the rubber concrete specimens were higher than those of reference concrete specimens at −30°C.

The relationship between the impact resistance and the rubber content of the rubber concrete specimens is detailed in Figure 2.

As can be seen in Figure 2, at both −30°C and 25°C, the incorporation of rubber powder had effectively improved the impact resistance of the rubber concrete specimens. Furthermore, as the rubber content of the concrete was increased from 0% to 20%, the impact resistance had also gradually increased. It was observed in this study that, with the increase in the rubber content in the concrete specimens, the elasticity of the concrete had become gradually improved. Then, as the cracks had developed from the inside areas of the specimens to the surface areas, the rubber powder was determined to have inhibited the generation and development of cracks. Therefore, the impact resistance of the specimens had been improved.

The relationship between the rubber content and impact times of the rubber concrete specimens is detailed in Figure 3.

Table 8: Impact test results for the rubber concrete specimens at 25°C.

Specimen number	Initial crack impact time ($\overline{N_1}$)	Ultimate crack impact time ($\overline{N_2}$)	Ductility index	Impact energy (J)	Initial crack relative value (%)	Ultimate crack relative value (%)
NC-0.40	14	20	1.43	88.2	100	100
RC-20-5	25	38	1.52	167.6	178.6	190
RC-20-10	31	48	1.55	211.7	221.4	240
RC-20-15	40	63	1.58	277.8	285.7	315
RC-20-20	47	75	1.6	330.8	335.7	375
RC-50-5	21	31	1.48	136.7	150	155
RC-50-10	28	43	1.54	189.6	200	215
RC-50-15	35	55	1.57	242.6	250	275
RC-50-20	41	65	1.59	286.7	292.8	325

Table 9: Impact test results for the rubber concrete specimens at −30°C.

Specimen number	Initial crack impact time ($\overline{N_1}$)	Ultimate crack impact time ($\overline{N_2}$)	Ductility index	Impact energy (J)	Difference between the initial and ultimate cracks	Initial crack relative value (%)	Ultimate crack relative value (%)
NC-0.40	10	13	1.3	57.33	3	100	100
RC-20-5	20	30	1.49	132.3	10	200	230.8
RC-20-10	27	41	1.51	185.2	14	270	323.1
RC-20-15	32	50	1.56	220.5	18	320	384.6
RC-20-20	37	58	1.57	255.8	21	370	446.2
RC-50-5	19	27	1.42	119.1	8	190	207.7
RC-50-10	24	35	1.46	154.4	11	240	269.2
RC-50-15	30	45	1.5	198.5	15	300	346.2
RC-50-20	39	60	1.54	264.6	21	390	461.5

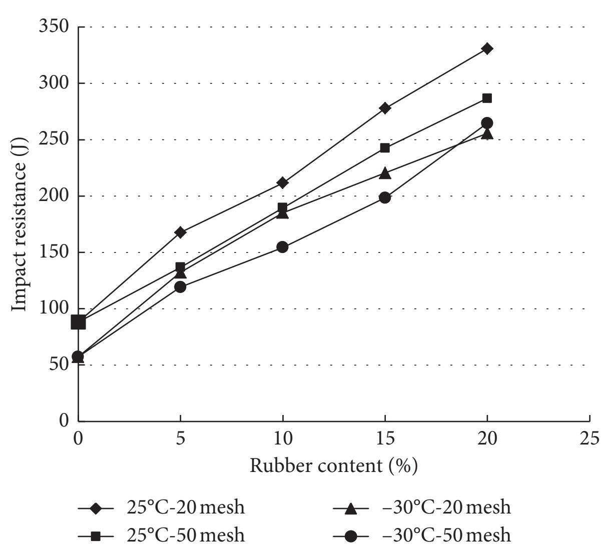


Figure 2: Relationship between the impact resistance and rubber content of the rubber concrete specimens.

As can be seen in Figure 3, the initial and ultimate crack impact times of the rubber concrete specimens at −30°C were lower than those at 25°C. However, the decreased amplitudes of the rubber concrete specimens were lower than those of the reference concrete specimens. The initial crack impact times of the rubber concrete RC-20-10 were 31 at 25°C and 27 at −30°C, which indicated a decrease of 12.9%. The initial crack impact times of the reference concrete NC-0.40 were 14 at 25°C and 10 at −30°C, which indicated a decrease of 28.5%. Moreover, it was observed that, at −30°C, the decreased reductions in the amplitudes of the initial crack impact times of the rubber concrete were approximately 50%, when compared with the reference concrete specimens. Therefore, the results of this study's experimental tests had indicated that the additions of rubber powder had significant effects on the impact resistance of the concrete specimens under low-temperature conditions (−30°C). It was found that when the rubber content had been increased from 0% to 20%, the differences between the initial and ultimate crack impact times had also increased significantly.

The relationships between the rubber particle sizes (mesh) and ductility indexes of the concrete specimens are shown in Figure 4.

Ductility indexes are the relative values which accurately reflect the deformation performances of a material. As can be seen in Figure 4, at both 25°C and −30°C, the ductility index of the rubber concrete with 20 mesh rubber powder was greater than that with 50 mesh rubber powder. Therefore, it was concluded that the rubber concrete with rubber power of a smaller particle size had a lower bulk density and a larger internal surface area. The rubber concrete with smaller rubber particle sizes had also contained more gas and initial defects. It could then be assumed that the rubber concrete with larger rubber particle sizes had better impact resistance.

As detailed in Figure 4, the ductility indexes of both rubber concrete and reference concrete specimens at −30°C were lower than those at 25°C. The decreased amplitudes of the ductility indexes of the rubber concrete specimens were found to be lower than those of the reference concrete, which

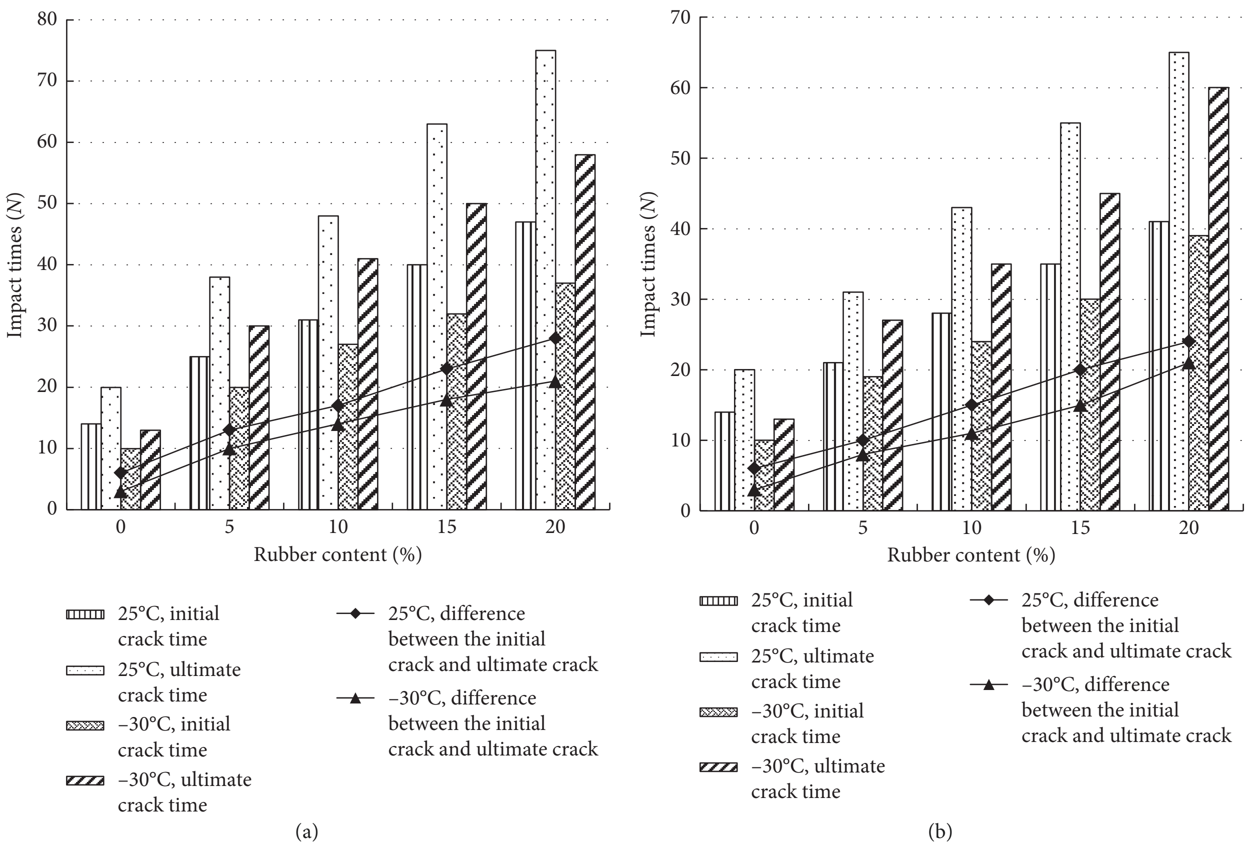


Figure 3: Relationship between the rubber content and impact times of the rubber concrete specimens. Rubber powder: (a) 20 mesh and (b) 50 mesh.

indicated that the additions of rubber powder could effectively alleviate the brittleness of the concrete specimens. It was observed in this study that when the rubber content levels of the RC-20 concrete were 5%, 10%, 15%, and 20%, the ductility indexes at −30°C had decreased by 5.7%, 2.6%, 3.4%, and 1.9%, respectively, when compared with those at 25°C. Meanwhile, the ductility indexes of the RC-50 concrete had decreased by 4.1%, 5.2%, 4.5%, and 3.1%, respectively. It was determined that, for the specimens with the same rubber content, the extent of the reductions in the ductility indexes of the concrete specimens with large rubber particle sizes were lower under the lower temperature conditions (−30°C). Furthermore, it was observed that, at −30°C, when the rubber content was 20%, the extent of the reductions in the ductility indexes of the rubber concrete was the least.

4.2. Distribution Characteristics of the Impact Times. During the past few years, the fatigue test data of material have often been analyzed using normal distributions and lognormal distributions [31, 32]. However, the lognormal distributions are risk functions, and when a material's life exceeds a specific value, the probability of its failure will tend to decrease with time. However, this property does not correspond to the physical properties of material which are subjected to impacts and dynamic loading in the field of engineering. In the current available related literature [33, 34], it was indicated that the impact resistance levels of steel fiber high-strength concrete and fiber concrete had been previously examined using drop-weight test methods. However, the experimental results had not obeyed normal distributions. Also, some researchers have conducted further research and have determined that the fatigue life of concrete could be more suitable as described by using the Weibull distribution method [35]. The Weibull distribution method includes an increasing hazard function with time and is most commonly used for describing fatigue data. Due to the similarity between the failure mechanisms of the currently used impact tests and fatigue tests, the Weibull distribution method has been adopted as a method for the statistical analyses of impact test data.

The Weibull distribution function is characterized by a probability density function $f(N)$ as indicated in the following equation:

$$f(N) = \frac{b}{N_a - N_0}\left[\frac{N - N_0}{N_a - N_0}\right]^{b-1} \cdot \exp\left[-\left(\frac{N - N_0}{N_a - N_0}\right)^{b}\right], \quad (N_0 \leq N \leq \infty), \tag{2}$$

where N_a represents the scale parameters, N_0 denotes the parameters of the minimum impact lifetime, and b is the shape parameters.

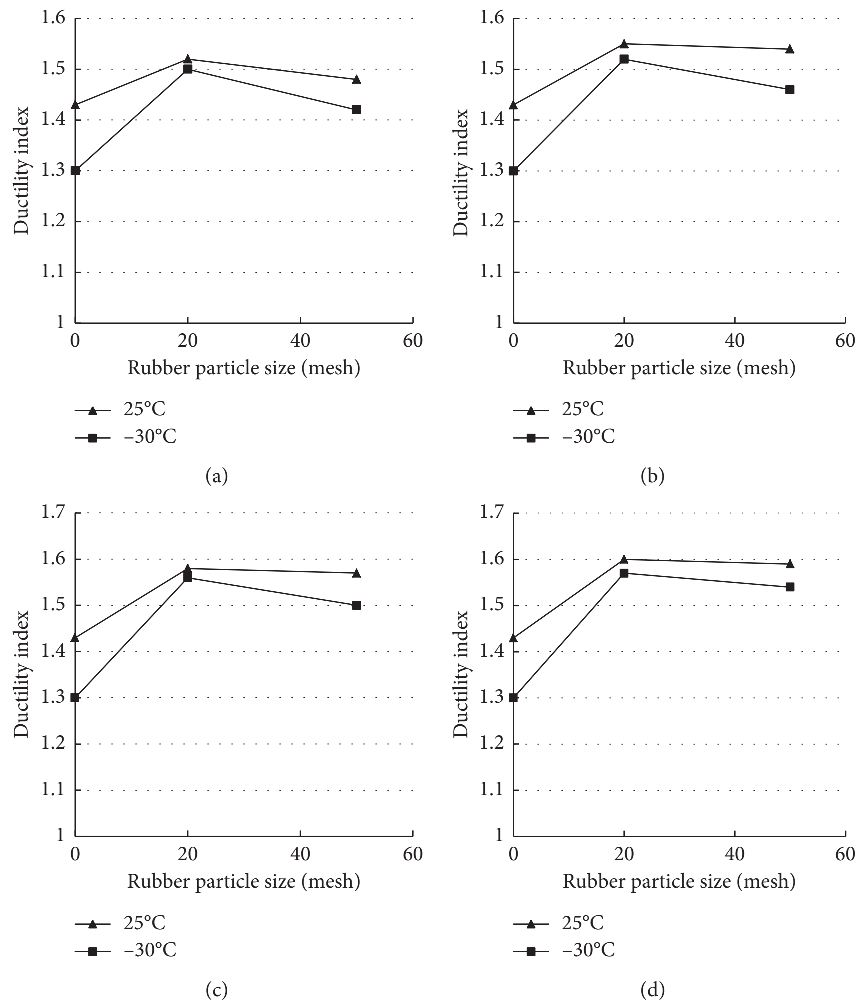


Figure 4: Relationship between the rubber particle sizes and the ductility indexes of the concrete specimens. Rubber content: (a) 5%, (b) 10%, (c) 15%, and (d) 20%.

Due to the discreteness of the concrete strength and in consideration of the safety and reliability of the material, the minimum impact lifetime may be set as $N_0 = 0$. Then, the probability density function of the Weibull distribution function can be simplified as shown in the following equation:

$$f(N) = \frac{b}{N_a}\left[\frac{N}{N_a}\right]^{b-1}\exp\left[-\left(\frac{N}{N_a}\right)^{b}\right], \quad (N_0 \le N \le \infty). \tag{3}$$

The cumulative failure probability function can then be obtained by the integration of the probability density function, as shown in the following equation:

$$P(N) = 1 - \exp\left[-\left(\frac{N}{N_a}\right)^{b}\right]. \tag{4}$$

The following reliability function can be obtained using equation (4):

$$R(N) = 1 - P(N) = \exp\left[-\left(\frac{N}{N_a}\right)^{b}\right]. \tag{5}$$

Then, the following relationship can be obtained by taking the natural logarithms of both sides of equation (5):

$$\ln\left\{\ln\left[\frac{1}{R(N)}\right]\right\} = b\ln(N) - b\ln(N_a). \tag{6}$$

Set $Y = \ln\{\ln[1/R(N)]\}$, $X = \ln(N)$, and $C = -b\ln(N_a)$, and then equation (6) can be written as follows:

$$Y = bX + C. \tag{7}$$

If X and Y have an approximate linear relationship, then it can be demonstrated that the impact times of the rubber concrete obey the Weibull distribution. Then, the regression coefficients of b, $b\ln(N_a)$, and the correlation coefficient R^2 corresponding to all of the concrete samples can be successfully obtained from the results of the regression analysis.

Table 10: Linear regression coefficients of the impact resistance in the Weibull distributions at 25°C and −30°C.

Impact times	Specimen number	25°C			−30°C		
		b	$b\ln(N_a)$	R^2	b	$b\ln(N_a)$	R^2
N_1	NC-0.40	2.756	7.615	0.956	1.694	4.261	0.947
	RC-20-5	2.250	7.554	0.980	2.184	7.120	0.880
	RC-20-10	2.197	7.855	0.972	2.846	10.030	0.998
	RC-20-15	3.294	12.520	0.982	2.693	9.675	0.978
	RC-20-20	3.910	15.440	0.843	2.707	10.120	0.961
	RC-50-5	1.500	4.801	0.976	2.715	8.335	0.973
	RC-50-10	2.343	8.151	0.900	2.801	8.687	0.988
	RC-50-15	1.547	5.764	0.976	2.936	10.340	0.977
	RC-50-20	3.713	14.180	0.996	3.247	12.260	0.956
N_2	NC-0.40	3.623	11.230	0.982	2.588	7.497	0.940
	RC-20-5	2.750	10.350	0.979	2.699	9.523	0.902
	RC-20-10	3.822	15.180	0.969	3.627	13.84	0.965
	RC-20-15	5.094	21.510	0.952	4.652	18.600	0.927
	RC-20-20	7.212	31.570	0.943	4.107	17.070	0.910
	RC-50-5	1.819	6.529	0.942	3.172	10.650	0.946
	RC-50-10	3.199	12.400	0.991	2.786	10.190	0.934
	RC-50-15	2.482	10.290	0.948	5.059	19.660	0.985
	RC-50-20	5.091	21.630	0.964	3.829	16.060	0.976

In the current study, the verification process was divided into two steps. First, the data of the impact resistance (N_1 and N_2) of eight specimens in each group were arranged in the ascending order, and the order numbers (i) were recorded. Second, the expectation estimations of the functions $P(N)$ and $R(N)$ were adopted in order to calculate the values of the cumulative invalid probability functions and the survivorship functions. The expectation estimations of the functions $P(N)$ and $R(N)$ were as follows:

$$P(N) = \frac{i}{(n+1)}, \tag{8}$$

$$R(N) = 1 - \frac{i}{n+1}, \tag{9}$$

where i represent the order number and n is the total number of specimens.

In this study, at −30°C, the number of impacts N_1 and N_2 of the specimens was calculated according to equations (7)–(9). Then, the least squares method was used for the linear regression. The regression coefficients of b, $b\ln(N_a)$, and the correlation coefficient R^2 are detailed in Table 10. The regression line graphs of the impact times of the rubber concrete specimens at 25°C and −30°C were plotted between $\ln\{\ln[1/R(N)]\}$ and $\ln(N)$, as shown in Figures 5 and 6.

As can be seen in Table 10, at 25°C, the minimum value of R^2 was 0.843 and the maximum value of R^2 was 0.996. However, at −30°C, the minimum value of R^2 was 0.88 and the maximum value of R^2 was 0.998. It was observed that the values of the majority of the correlation coefficients R^2 were greater than 0.9, which confirmed that $\ln\{\ln[1/R(N)]\}$ and $\ln(N)$ had a linear relationship.

As detailed in Figures 5 and 6, the data points had fallen approximately along a straight line. Therefore, these results had indicated that the two-parameter Weibull distribution method had accurately described the distribution law of the impact times of the rubber concrete specimens at both 25°C and −30°C.

4.3. Estimations of the Impact Life of the Concrete Specimens Undergoing Different Failure Probabilities. In the current study, in accordance with the results of equations (5)–(8), a two-parameter Weibull distribution method was adopted to describe the relationship between the impact times and the rubber content specimens. The relationship between the impact times N and the failure probability P could be expressed as follows:

$$N = \exp\left\{\frac{\ln[\ln(1/1-p)] + b\ln(N_a)}{b}\right\}. \tag{10}$$

The failure probability can also be estimated according to the Bayes nmethod described by Jia et al. [36], which was taken as between 0 and 0.5. In this study, the three failure probabilities 0.1, 0.2, and 0.3 were taken for the evaluations. Then, under the different failure probabilities, the initial and ultimate crack impact times of the rubber concrete specimens at 25°C and −30°C were calculated according to equation (10). The results of the impact times are detailed in Table 11.

In the present study, in order to analyze the relationship between the impact times and the rubber content under different failure probability conditions, the logarithm value of the initial crack impact times was taken as the Y-axis and the value of the rubber content was taken as the X-axis. Meanwhile, the logarithm value of the ultimate crack impact times was taken as the Y-axis, and the value of the rubber content was taken as the X-axis. The relationships between $\ln N$ and V_R under the different failure probability conditions were established according to the data detailed in Table 11. The results are presented in Figures 7 and 8.

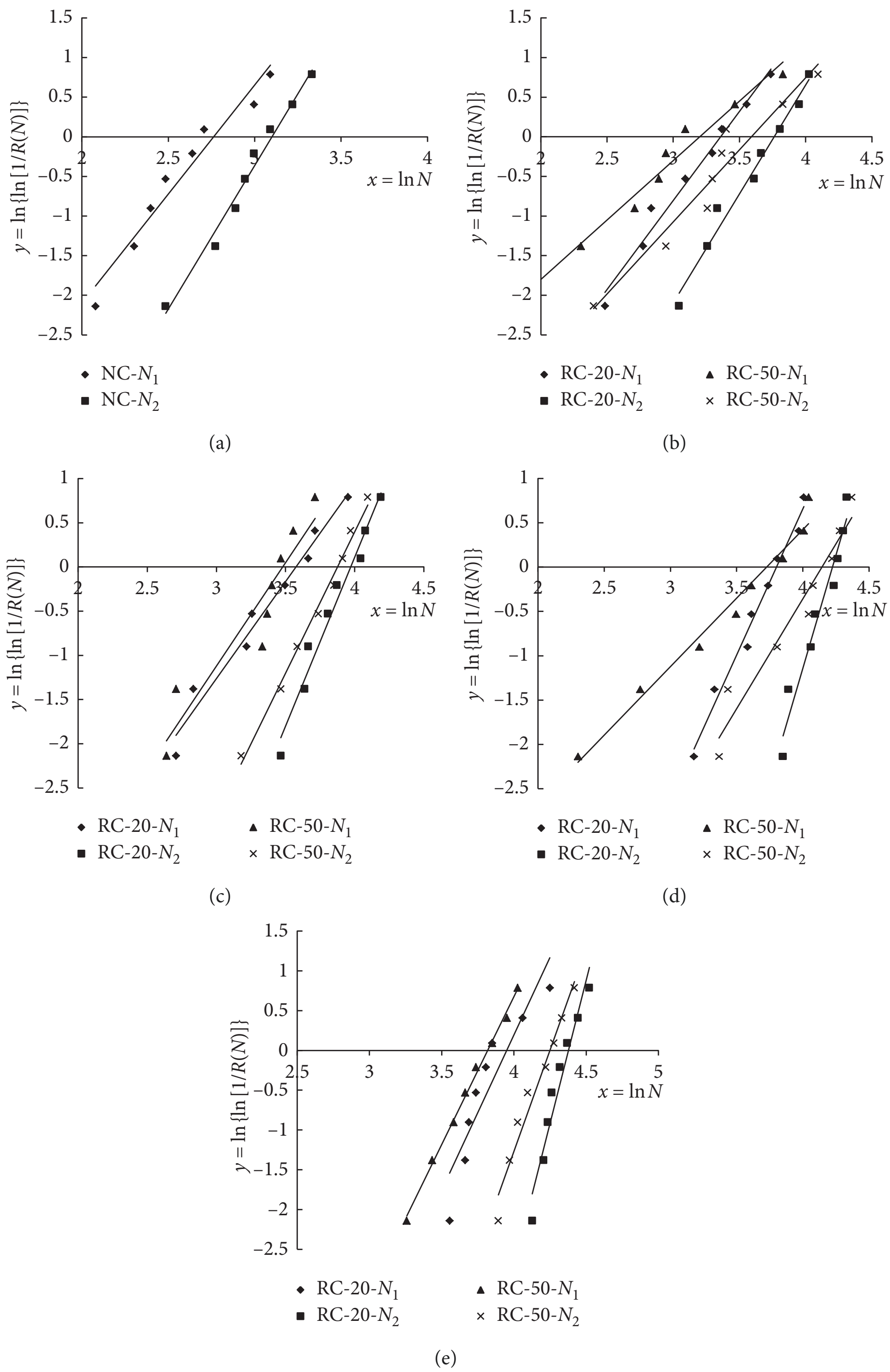


Figure 5: Weibull distributions of N for the rubber concrete specimens at 25°C. Rubber powder: (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%.

As can be seen in Figures 7 and 8, when the failure probability was a constant, the number of impacts on the rubber concrete was approximately linear with the rubber content. When the rubber particle sizes and failure probability were constants, the initial and ultimate crack impact times were determined to be approximately three times that of the reference concrete specimens, which indicated that the rubber concrete had displayed a higher impact resistance.

5. Conclusions

In the current study, the impact resistance performances of rubber concrete specimens were evaluated by conducting impact tests. The four useful findings achieved in this study were summarized as follows:

(1) It was found that the initial and final crack impact times of the rubber concrete specimens at −30°C

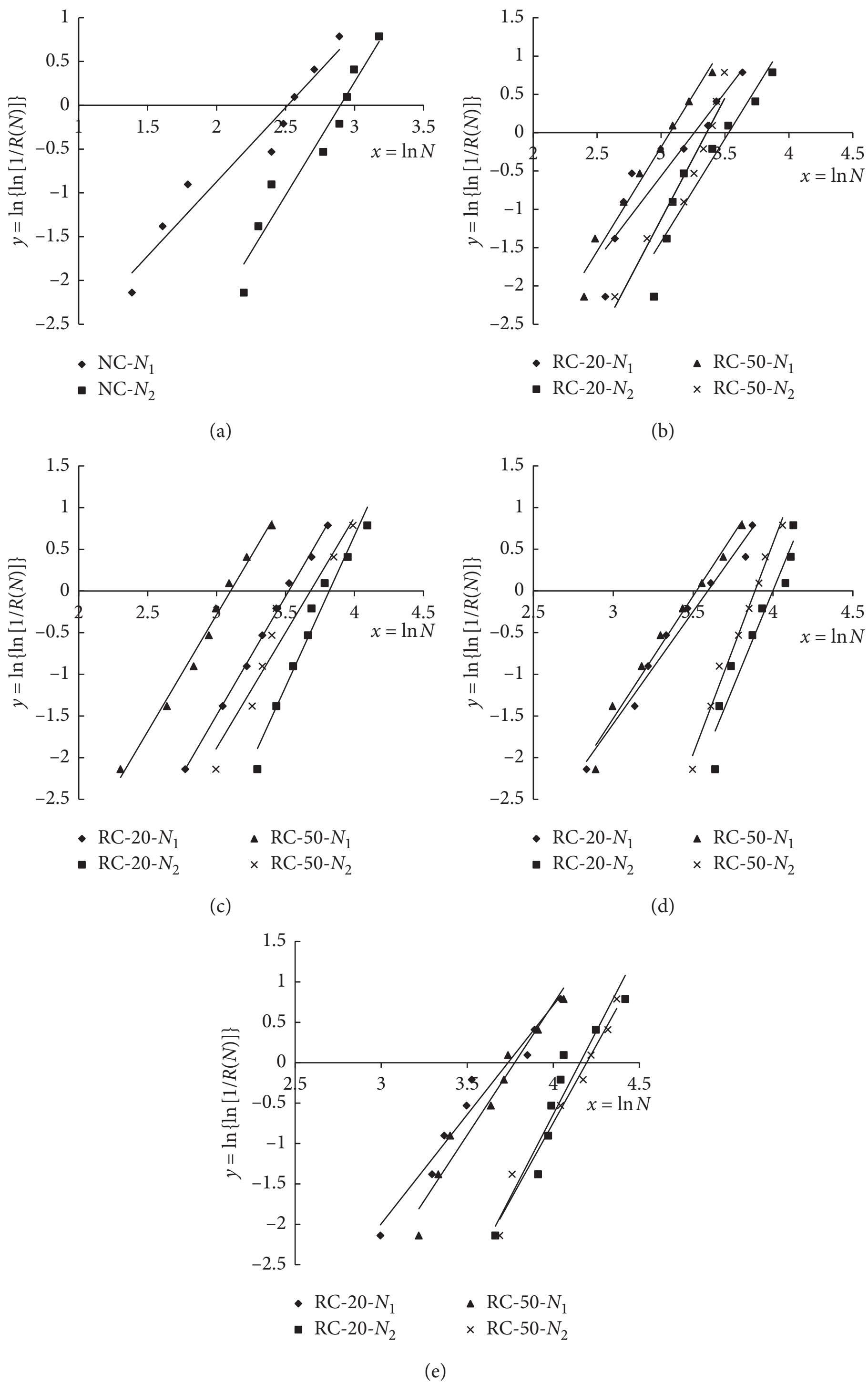


Figure 6: Weibull distributions of N for the rubber concrete specimens at −30°C. Rubber powder: (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%.

were lower than those at 25°C. However, the decrease amplitudes of the rubber concrete had been reduced by 50% when compared with the reference concrete specimens. The results indicated that the additions of rubber powder had significant effects on the ductility of the concrete at low temperatures (−30°C). When the rubber content had been increased from 0% to 20%, the differences between the initial and ultimate crack impact times were also significantly increased.

(2) The ductility indexes of the rubber concrete specimens and the reference concrete specimens at −30°C were determined to be lower than those at 25°C. In addition, the decrease amplitudes of ductility indexes of the rubber concrete specimens were lower than

Table 11: Impact times of the rubber concrete specimens under different failure probability conditions.

Failure probability	Specimen number	25°C N_1	25°C N_2	−30°C N_1	−30°C N_2
0.1	NC-0.40	7	12	3	8
	RC-20-5	11	19	9	15
	RC-20-10	13	29	12	24
	RC-20-20	29	58	18	47
	RC-50-5	6	10	5	14
	RC-50-10	12	23	10	17
	RC-50-15	20	31	16	31
	RC-50-20	25	45	22	37
0.2	NC-0.40	9	15	5	10
	RC-20-5	15	25	13	20
	RC-20-10	18	36	20	30
	RC-20-15	28	51	26	40
	RC-20-20	35	65	24	52
	RC-50-5	9	16	7	15
	RC-50-10	17	30	13	25
	RC-50-15	19	35	20	36
	RC-50-20	30	52	28	45
0.3	NC-0.40	11	17	7	12
	RC-20-5	18	30	16	23
	RC-20-10	22	41	24	34
	RC-20-15	33	56	31	44
	RC-20-20	40	69	29	57
	RC-50-5	12	21	10	17
	RC-50-10	21	35	15	30
	RC-50-15	28	42	24	40
	RC-50-20	35	57	32	51

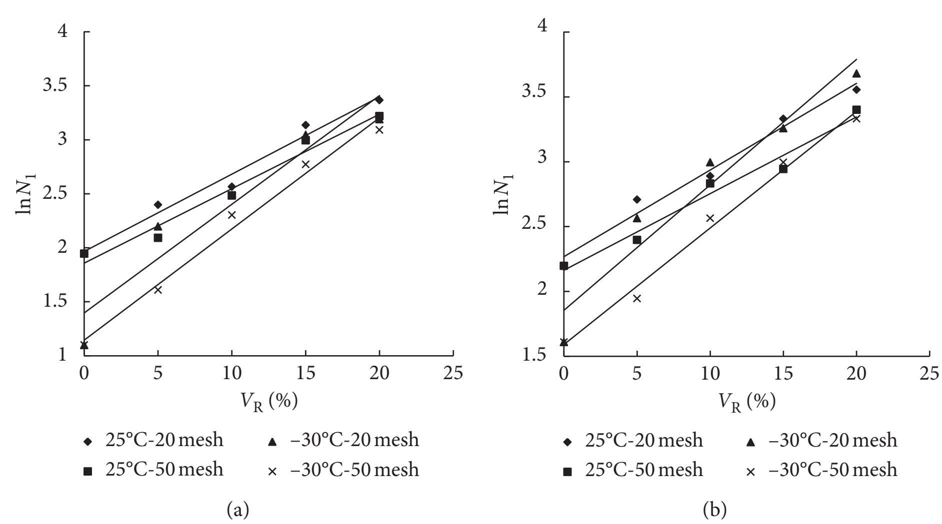
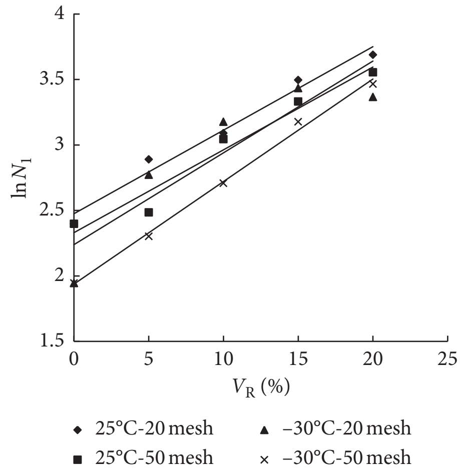
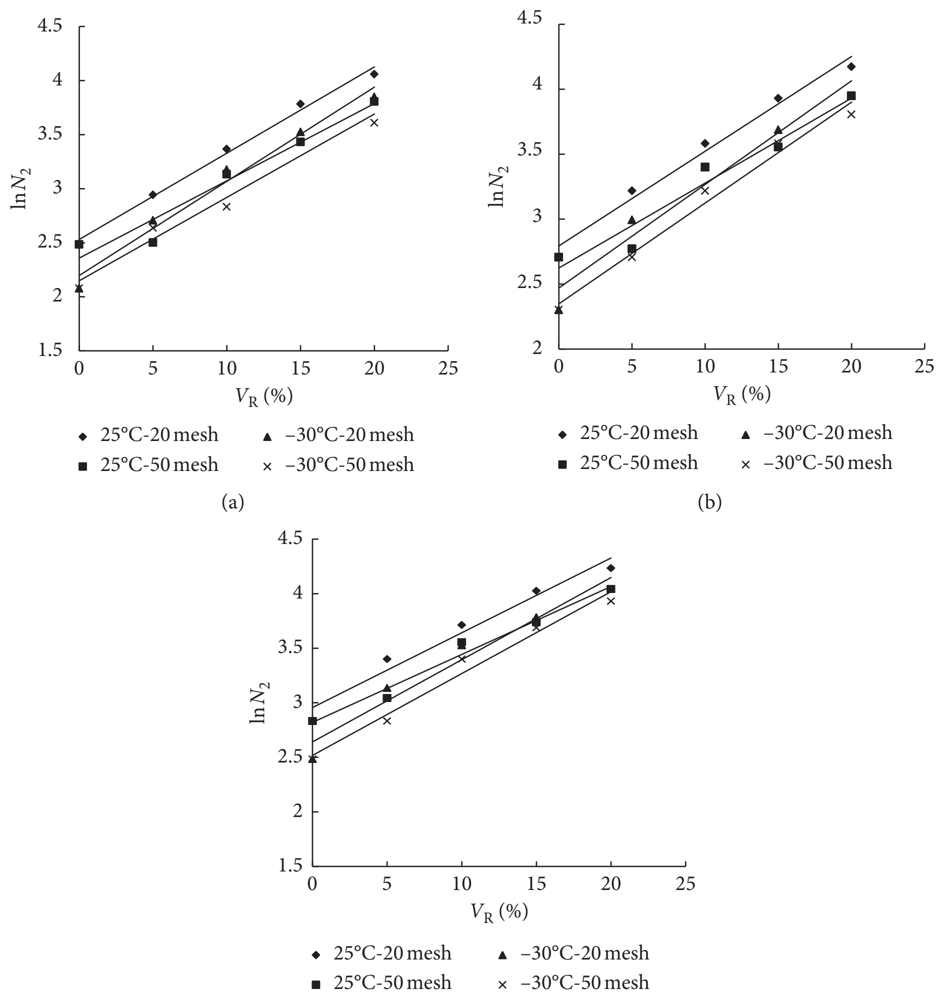


Figure 7: Continued.



(c)

Figure 7: Relationship between $\ln N_1$ and V_R. Failure probability is (a) 10%, (b) 20%, and (c) 30%.



(c)

Figure 8: Relationship between $\ln N_2$ and V_R. Failure probability is (a) 10%, (b) 20%, and (c) 30%.

those of the reference concrete specimens. The results indicated that the additions of rubber powder had significantly improved the ductility of the concrete specimens at low temperatures (−30°C). The decrease amplitudes of the ductility indexes of the rubber concrete specimens with 20 mesh rubber powder were found to be lower than the rubber concrete specimens with 50 mesh rubber powder at −30°C.

(3) The two-parameter Weibull distribution method was adopted to accurately describe the distribution law of the impact times of the rubber concrete specimens at both 25°C and −30°C.

(4) It was found that, by adopting the two-parameter Weibull distribution method, the function relationships between the impact times and the failure probabilities could be established by fitting the data. It was observed that when the failure probability was a constant, there was a good linear relationship between the impact times and the rubber content of rubber concrete specimens.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

There were no conflicts of interest to declare in this study.

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