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Evaluation of the Fatigue Performance of Full-Depth Reclamation with Portland Cement Material Based on the Weibull Distribution Model

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Abstract: The full-depth reclamation with Portland cement (FDR-PC) technology embodies an environmentally friendly approach to solving the damage to old asphalt pavement. Fatigue failure emerges as the predominant mode of degradation for FDR-PC pavement. The fatigue characteristics of the full-depth reclamation with Portland cement cold recycled mixtures were evaluated through four-point bending tests. Three contents (4%, 5%, 6%) of cement and three base-to-surface ratios (10:0, 8:2, 6:4) were utilized. The fatigue equations were derived for the mixtures using a two-parameter Weibull distribution. The results indicate that all correlation coefficients of the Weibull distribution model surpass 0.88, effectively projecting the lifespan of FDR-PC. With increases in cement contents and base-to-surface ratios, the fatigue life of the mixture extends, though with an augmentation of stress sensitivity. Comparative analysis with the fatigue equation model parameters of the current Chinese specifications for the design of highway asphalt pavement reveals that mixtures with a 4% cement content and combinations of a 5% cement content with a low base-to-surface ratio meet the requirements for inorganic-binder-stabilized soil. Additionally, mixtures with a 5% cement content and a high base-to-surface ratio, along with those with a 6% cement content, fulfill the specifications for inorganic-binder-stabilized granular materials.

Keywords: full-depth reclamation with Portland cement; four-point bending test; Weibull distribution; fatigue equation

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1. Introduction

With the rapid surge in road construction, addressing the repair of deteriorating roads has become imperative. Given the global challenges posed by climate change and economic factors, current endeavors in road construction and repair are primarily focused on harnessing substantial quantities of solid waste while augmenting the technical efficacy of road materials [1,2]. In China's regular highways, asphalt pavements are typically relatively thin, ranging from 4 cm to 8 cm in thickness, thereby leading to damage patterns predominantly characterized by a combination of asphalt surface deterioration and base-layer degradation. Recycled materials primarily sourced from the old subgrade will pose challenges in terms of complex construction and cost-effectiveness if the old asphalt surface and base materials are categorized and reapplied separately. Therefore, full-depth cold recycling technology aligns exceptionally well with projects involving the conversion of regular highways' thin asphalt layers, addressing intricacies and enhancing cost-effectiveness.

The full-depth reclamation with Portland cement (FDR-PC) is a cold recycling technology developed for old asphalt pavement, with its origins traced back to the United

States and France in the 1950s [3,4]. The FDR-PC technique initiates with the utilization of on-site milling equipment to disintegrate the old pavement, proportionally mixing the reclaimed asphalt and base layers. After this phase, cement is introduced and uniformly blended, and then it is compacted to generate a new composite material [5]. Compared to alternative restoration methods, FDR-PC demonstrates superior mechanical properties, a shorter construction duration, minimal traffic disruption, cost-effectiveness, and reduced carbon emissions [6,7].

Although a new material, FDR-PC falls under the category of stable inorganic mixtures and is utilized as a base layer in reconstructed asphalt pavements. As is widely acknowledged, the fatigue performance of the base layer plays a crucial role in determining the overall design life of semi-rigid-base asphalt pavement structures. Fatigue failure is the predominant mode of structural deterioration in full-depth reclamation of pavement. The mixture design methods proposed in various countries, including the United States [8], Spain [9], Germany [10], South Africa [11], Australia, New Zealand [12], and Brazil [13], consistently emphasize the need for durability testing in addition to the 7-day unconfined compressive strength test during the design phase. In laboratory research, when focusing on the impact of reclaimed asphalt pavement (RAP), Jiang [14] observed that a higher RAP content decreases the fatigue life of FDR-PC mixtures. López [15] proposed that the influence of the RAP content on the fatigue behavior of the mixtures is intricate and necessitates a consideration of the cement content and layer thickness. When considering the impact of cement, Guthrie [16] and Yuan [17] highlighted that an increased cement content enhances the strength and stiffness of FDR-PC mixtures. Dixon [18] emphasized that cement improves durability by reducing the sensitivity to water, while Fedrigo [19] indicated that a high cement content enhances durability but may raise the risk of shrinkage, requiring usage restrictions. López [15] conducted a comprehensive study on the impact of RAP and cement on the fatigue properties of FDR-PC mixtures.

In field research, Syed [20] conducted on-site assessments of 75 highway projects in the United States, unveiling the stability and cost-effectiveness of FDR-PC during long-term use. However, in general, the existing research on the fatigue properties of FDR-PC mixtures is not comprehensive. Furthermore, considering the stochastic and discrete nature of concrete life, research methods employing linear regression and mean values have limitations. Therefore, noting the current scarcity of statistical and probabilistic approaches in existing studies, in this study, we utilized a two-parameter Weibull distribution for statistical and probabilistic investigations into the fatigue properties of FDR-PC.

The fatigue life of pavement materials exhibits stochasticity and discreteness. Their lifespan is influenced by various factors such as the concrete mix proportion, strength, and environmental conditions, all of which possess inherent randomness. Additionally, the strength of concrete is discretely distributed; even in specimens composed of concrete with well-controlled quality, the strength varies within a certain range [21]. Concrete lifespan experiments typically involve small sample sizes, rendering linear regression analysis susceptible to significant noise interference. To mitigate the impact of the discreteness of test data on the results of fatigue performance analysis, increasing the sample size is an effective solution. However, fatigue tests typically consume significant time, leading to a substantial increase in testing costs. Constrained by these factors, current laboratory fatigue tests for asphalt mixtures often utilize a limited number of specimens. Therefore, to accurately analyze the fatigue performance of asphalt mixtures with a small sample size, statistical analysis methods are essential.

The Weibull distribution stands as the foundational theory for reliability analysis and lifespan testing, providing a continuous probability distribution capable of modeling increasing, decreasing, or fixed failure functions. This model facilitates the description of any stage in the project lifespan and is extensively applied in reliability engineering [22–24]. Its proficiency in inferring distribution parameters using probability values makes it a widely employed tool in processing data from various lifespan tests [24]. In investigating the lifespan of concrete, Guo [25] utilized the dynamic modulus as a durability assessment indicator, revealing that stochastic analysis methods employing both two-parameter and three-parameter Weibull distributions effectively assess the degradation process of concrete in the Xining region in China. Wang [26], relying on the Weibull distribution model, established an impact damage prediction model for ultra-high-performance concrete. They analyzed the model's precision using the decision coefficient R^2, thereby effectively reflecting the damage development process of concrete under freeze–thaw and impact environments. Wang's [27] research suggests that the Weibull distribution enables researchers to reduce the number of tests and articulate the impact failure strength of fiber-reinforced concrete from the perspectives of reliability and safety limits. Sun [28] applied a two-parameter Weibull distribution to describe the fatigue life distribution of asphalt concrete under varying conditions, demonstrating its relevance in observing material and environmental variations in laboratory experiments. Zhu [29] derived the damage evolution equation for alkali-resistant glass-fiber-reinforced concrete based on the Weibull distribution. These studies emphasize the extensive applicability and reliability of the Weibull distribution in concrete lifespan research.

Therefore, this study initiated the utilization of the full-depth reclamation with Portland cement cold recycled mixture, designed through the heavy compaction method. Following this, specimens were manufactured for four-point bending fatigue tests. To account for the stochastic and discrete characteristics of recycled mixture 's lifespan, a two-parameter Weibull distribution was employed to optimize the fit of the fatigue equation. Subsequently, the fatigue equation was used to explore the stress sensitivity and lifespan limits of the cold recycled mixture across different cement contents and base-to-surface ratios.

2. Materials and Methods

2.1. Raw Materials

The reclaimed materials originated from the 110 National Highway in Inner Mongolia in China, which serves as a secondary road network. The prevailing asphalt surface layer measured 4 cm and was composed of AC-16 asphalt mixture, while the base layer consisted of a 20 cm layer of cement-stabilized crushed stone.

The intricate challenge of segregating reclaimed asphalt pavement (RAP) and reclaimed inorganic-binder-stabilized aggregate (RIA) led, drawing upon construction expertise, to the decision to employ a milling machine for the stratified milling of both the old asphalt surface layer and the base layer. Subsequently, RAP and RIA underwent separation and extraction, followed by individual sieving post natural drying in the laboratory. To ensure precision in the gradation of blended recycled materials and minimize experimental errors, a systematic classification of RAP and RIA was executed, adhering to the criteria outlined in Table 1. The screening test results are visually presented in Figure 1.

Table 1. Results of screening test.

Sieve Size (mm)	37.5	31.5	26.5	19	9.5	4.75	2.36	1.18	0.6	0.075
RIA Passing Percentage (%)	100	99.7	96.3	80.4	56.7	36.1	24.7	18.4	13.4	4.7
RAP Passing Percentage(%)	100	100	100	99.5	75.3	54.4	38.1	26.4	16.4	2.4

Considering factors such as the thickness ratio between the old asphalt pavement surface layer and base layer, actual construction conditions, and economic considerations, it is common practice to limit the mass proportion of reclaimed asphalt pavement in full-depth recycling mixtures to a maximum of 40%. Consequently, three representative mineral compositions were devised for the experimentation, with base-to-surface ratios of 10:0, 8:2, and 6:4, respectively. As a result of these experiments, three distinct gradation curves were obtained for recycled materials. The synthesized gradation curve is illustrated in Figure 2.

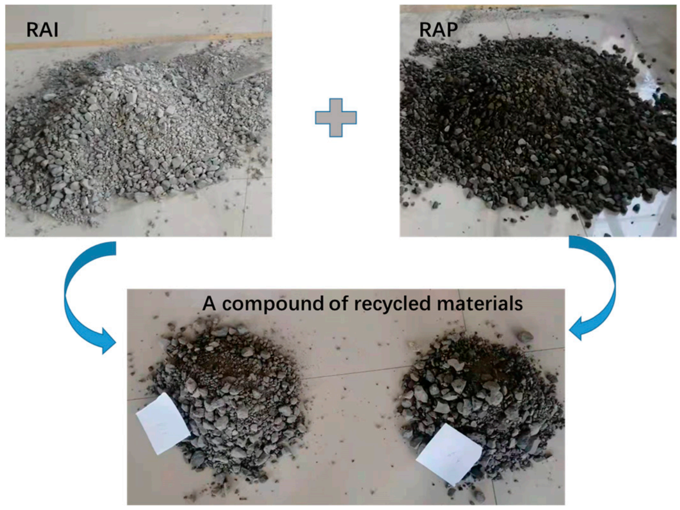


Figure 1. Reclaimed material.

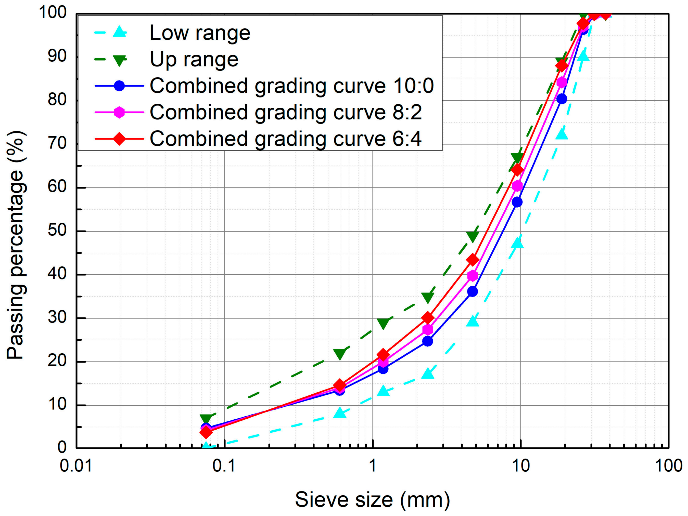


Figure 2. Synthesized gradation curve of FDR-PC cold recycled mixture, where the base-to-surface ratios are 10:0, 8:2, and 6:4.

The cement employed was ordinary Portland cement, graded at 42.5. The technical specifications are detailed in Table 2, adhering to the technical prerequisites stipulated in the Chinese specification JTG/T 5521—2019 [30].

Table 2. Technical indicators of cement.

Testing Item		Technical Indicator	Testing Result	Testing Method
Setting Time (min)	Initial Setting	≥180	218	GB/T 1346-2011 [31]
	Final Setting	≤600	385	
Flexural Strength (MPa)	3 d	≥3.5	3.8	GB/T 17671-2021 [32]
	28 d	≥6.5	10.6	
Compressive Strength (MPa)	3 d	≥17.0	19.9	
	28 d	≥42.5	45.5	

2.2. Determining the Optimum Water Content and the Maximum Dry Density

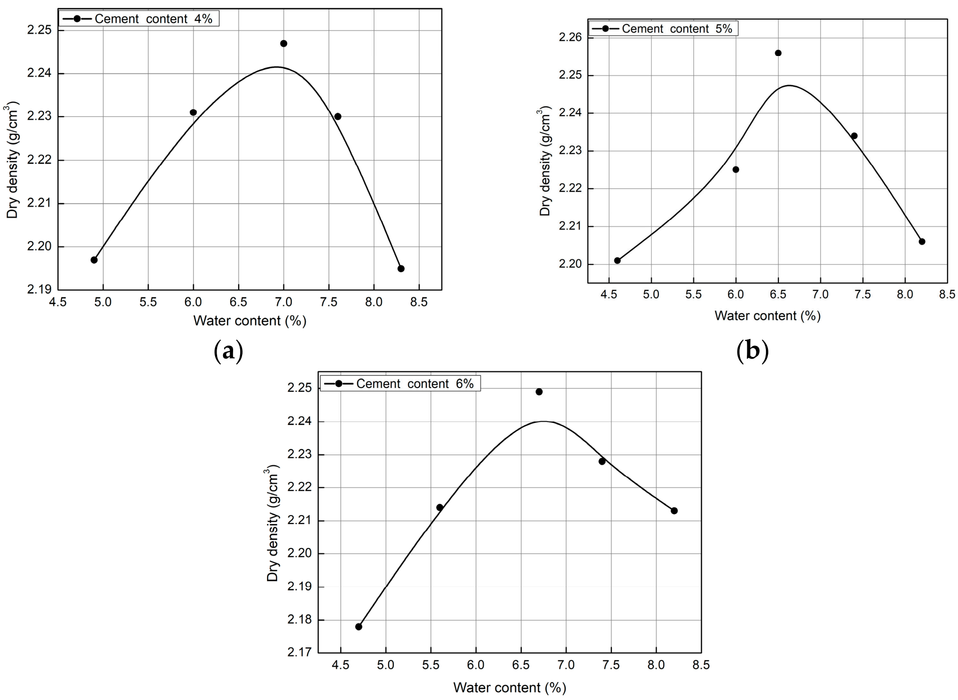
The heavy compaction test was employed to ascertain the optimal water content and the maximum dry density of FDR-PC cold recycled mixtures. The parameters and operational procedures were taken from the Chinese standard JTG E51-2009 [33].

The testing process involved the formation of 5 parallel specimens for each mixture, with each specimen being tested under varying moisture content levels. Cylinder specimens were produced by employing the static compaction method, with the size of 150 mm radius and 120 mm height. The production of a specimen's required weight in FDR-PC was determined by the compaction degree, the optimal water content, and the maximum dry density, as specified in Equation (1). All specimens underwent curing in a standard curing room, maintaining an air temperature of 20 ± 2 °C and a relative humidity of 95%.

$$m_0 = V \times \rho_{\max} \times \left(1 + w_{opt}\right) \times K, \tag{1}$$

In Equation (1), m_0 signifies the weight of an individual specimen, g; V denotes the volume relative to a single specimen, cm^3; $\rho_{\max}$ represents the maximum dry density, g/cm^3; w_{opt} indicates the optimum water content, %; and K denotes the compaction degree, with this paper adopting a compaction degree value of 98%.

Specimens were fabricated using cement contents of 4%, 5%, and 6% relative to the mass of the recycled mixture, resulting in distinct curves for dry density–water content, as depicted in Figure 3. The optimum water content and maximum dry density were derived from the vertex of each curve, as depicted in Table 3.



(c)

Figure 3. Dry density–water content curves of the full-depth cold recycled mixture. The base-to-surface ratio is 8:2. (**a**) 4% cement content; (**b**) 5% cement content; (**c**) 6% cement content.

Table 3. The optimum water contents and the maximum dry densities of specimens fabricated with the five different cement content and base-to-surface ratio combinations.

Cement Content (%)	Base-to-Surface Ratio	Optimal Water Content (%)	Maximum Dry Density (g/cm^3)
4	8:2	5.9	2.242
5	8:2	6.6	2.246
6	8:2	6.8	2.240
5	10:0	7.1	2.236
5	6:4	6.2	2.250

2.3. Flexural Strength Test Method

The load levels for the fatigue tests were determined based on the flexural strength. Each test group employed 12 specimens, with dimensions measuring 100 mm × 100 mm × 400 mm and a curing time of 90 days. Adhering to the Chinese specification JTG E51-2009 [33], as per T0851-2009, the specimens were positioned in fixtures, aligning the loading direction with the pressure direction during molding. The loading device and specimen utilized in the bending strength test were consistent with those employed in the fatigue test, as depicted in Figure 4. Rapid loading was applied at a rate of 50 mm/min, and the ultimate load P at the point of failure was recorded. The flexural strength was calculated using Equation (2).

$$f_{cf} = \frac{PL}{b^2 h}, \tag{2}$$

In the formula, f_{cf} signifies the flexural strength of the specimen, MPa; P denotes the ultimate load at the point of failure of the specimen, N; L represents the distance between the two supports, mm; b is the width of the specimen, mm; and h signifies the height of the specimen, mm.

Figure 4. The four-point bending test apparatus.

2.4. Fatigue Test Method

The fatigue performance of FDR-PC mixtures was evaluated using the experimental method specified in JTG E51-2009 [33], specifically T0856-2009, for assessing cement-stabilized materials. This ensured comparability of the experimental results and allowed for comparison with the fatigue equation parameters obtained from Chinese specifications. Each set comprised 6 specimens, undergoing standard curing for 90 days. Following the curing period, the specimens underwent 1 day of water immersion. Then, a four-point bending test was conducted using MTS, as illustrated in Figure 4. The span was set to 360 mm, with a horizontal distance of 60 mm between the two upper loading points and the beam center position, as well as a horizontal distance of 180 mm between the two lower support points and the beam center position.

The experiment was conducted in a stress-controlled mode with a loading frequency denoted by 10 HZ, utilizing a Haversine waveform as the loading pattern, as depicted in Figure 5. The stress characteristic formula was defined as

$$\lambda = \frac{P_{min}}{P_{max}} = 0.1, \tag{3}$$

where λ represents the stress characteristic value, P_{min} is the minimum stress, and P_{max} is the maximum stress.

Various stress levels were applied in the experiments to derive fatigue equations for each cold recycled mixture. Based on the flexural strength test results of different FDR-PC cold recycled mixture specimens, the specific loading scheme for the fatigue tests was determined, as outlined in Table 4.

Each experiment commenced with 1 min preloading at 0.2 times the stress intensity ratio level, to prevent a rapid increase in test loads. Subsequently, the fatigue test proceeded until specimen failure, automatically recording the number of cycles at the point of failure.

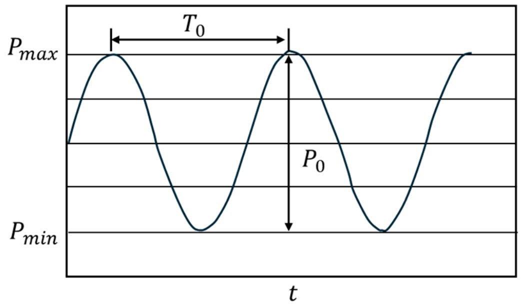


Figure 5. Haversine wave loading in fatigue tests.

Table 4. Loading schemes for FDR-PC cold recycled mixtures in fatigue tests.

Cement Content (%)	Base-to-Surface Ratio	Flexural Strength (MPa)	Stress Ratio	Maximum Load (N)	Minimum Load (N)
5	10:0	1.43	0.6	2850	285
			0.65	4000	400
			0.7	3350	335
			0.75	3575	358
			0.8	3800	380
	8:2	1.27	0.6	2540	250
			0.65	2750	275
			0.7	3000	300
			0.75	3175	320
			0.8	3400	340
	6:4	1.07	0.6	2150	215
			0.65	2300	230
			0.7	2500	250
			0.75	2675	270
			0.8	2850	285
4	8:2	0.87	0.6	1740	170
			0.65	1885	190
			0.7	2030	200
			0.75	2175	220
			0.8	2320	230
6	8:2	1.49	0.6	3000	300
			0.65	3250	320
			0.7	3500	350
			0.75	3725	370
			0.8	4000	400

2.5. Weibull Distribution

The fatigue damage of concrete is inherently a dynamic stochastic process. Consequently, even under identical test conditions and deterministic loading profiles, there is significant variability in the fatigue life of concrete specimens. In such circumstances, to obtain reliable fatigue performance data for cold recycled mixtures, the fatigue life can be treated as a random variable. The Weibull distribution has been widely employed in existing research to establish mathematical probability models for the fatigue life of civil engineering materials [34], particularly demonstrating strong adaptability to small sampling and various types of fatigue test data [35]. This study also utilized the two-parameter Weibull distribution to investigate the fatigue life of cold recycled mixtures. The probability density function $f(N)$ and cumulative distribution function $F(N)$ of the Weibull distribution can be expressed by Equations (4) and (5).

$$f(N) = \frac{\alpha}{N_a - N_0}\left(\frac{N - N_0}{N_a - N_0}\right)^{\alpha - 1} \cdot \exp\left[-\left(\frac{N - N_0}{N_a - N_0}\right)^{\alpha}\right](N \geq N_0) \tag{4}$$

$$F(N) = \int_{N_0}^{N} f(N)dN = 1 - \exp\left[-\left(\left(\frac{N - N_0}{N_a - N_0}\right)^{b}\right)\right] \tag{5}$$

where N is the experimental fatigue life, N_α is the characteristic life parameter, α is the Weibull shape parameter, and N_0 is the initial minimum life parameter.

The function $F(N)$, denoting the cumulative distribution function, signifies the probability that the fatigue life of a specimen is less than N. It can also be construed as the failure probability function for FDR-PC cold recycled mixtures. On the other hand, $1 - F(N)$ presents the reliability probability function for FDR-PC cold recycled mixtures, as delineated by Equation (6), signifying the probability that the fatigue life of a specimen exceeds N.

$$P(N) = 1 - F(N) = \exp\left[-\left(\frac{N - N_0}{N_a - N_0}\right)^{b}\right] \tag{6}$$

From a reliability perspective, considering the variability in the strength of cement-stabilized cold recycled mixtures and the variability in fatigue loads, it is assumed that the minimum fatigue life of cold recycled mixtures approaches 0. Therefore, the probability density function and $P(N)$ can be simplified to Equations (7) and (8).

$$f(N) = \frac{\alpha}{N_a}\left(\frac{N}{N_a}\right)^{\alpha - 1} \cdot \exp\left[-\left(\frac{N}{N_a}\right)^{\alpha}\right] \tag{7}$$

$$P(N) = \exp\left[-\left(\frac{N}{N_a}\right)^{\alpha}\right] \tag{8}$$

Furthermore, when taking the reciprocal of both sides of Equation (8) and subsequently applying two logarithmic transformations, the result is

$$\ln\left[ln\left(\frac{1}{p}\right)\right] = \alpha lnN - \alpha lnN_a \tag{9}$$

Let $Y = \ln\left[ln\left(\frac{1}{p}\right)\right]$, $\mathrm{X} = lnN$, and $\beta = \alpha lnN_a$, and then Equation (9) can be expressed as Equation (10).

$$Y = \alpha X - \beta \tag{10}$$

Equation (10) represents a linear equation, and the parameters α and β can be fitted from experimental data. If Y and X exhibit a strong linear relationship, this indicates that the two-parameter Weibull distribution model is suitable for fatigue life distribution. According to the probability distribution theory, in small samples, the mathematical expectation of the failure rate of a certain sample can be estimated using the average rank as an estimate of the survival rate of the small sample. When arranging n fatigue test data obtained from fatigue tests at the same stress level in ascending order, the serial number is represented by i, and the reliability P corresponding to the fatigue life N is calculated according to Equation (11).

$$P = 1 - \frac{i}{n+1}, \tag{11}$$

2.6. Fatigue Equation

The fatigue equation for concrete typically characterizes the fatigue performance of concrete under alternating loads. This equation can be formulated in the S-N curve representation, as depicted by Equation (12) [36].

$$\lg N = a - k\sigma/S, \tag{12}$$

In the equation, N signifies the number of loading cycles at failure, a represents the intercept of the curve, k denotes the slope of the curve, and σ/S stands for the stress ratio. When derived from Equation (12), it becomes apparent that the intercept a and slope k of the fatigue equation serve as pivotal indicators of the fatigue performance of the mixture. A heightened k value corresponds to a more pronounced fatigue curve, signifying an increased sensitivity of fatigue life to alterations in stress levels. Conversely, a mirrors the vertical placement of the fatigue curve, and an elevated a value implies a larger fatigue life limit.

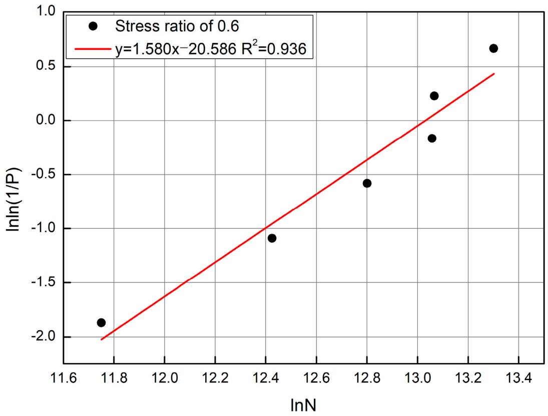
3. Results and Discussion

3.1. Fatigue Test Results

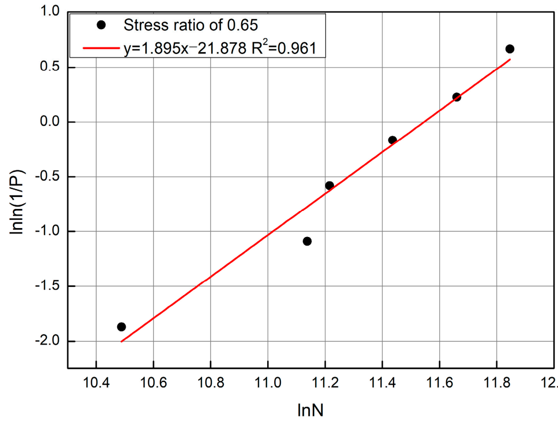
The fatigue life tests were conducted on cold recycled mixtures with cement content and base-to-surface ratio combinations of 4%–8:2, 5%–8:2, 6%–8:2, 5%–6:4, and 5%–10:0. The reliability-life results for various parameter combinations under different stress ratios are presented in Table 5. The P-N curves for the cold recycled mixture with a cement content of 5% and a base-to-surface ratio of 8:2, fitted through the Weibull distribution, are depicted in Figure 6. The correlation coefficients R^2 for the Weibull-distribution-fitted curves consistently exceed 0.88 in Table 5, indicating that the fatigue life of cold recycled mixtures conforms to the Weibull distribution.

Table 5. The fatigue test results for various mixtures under different stress ratios.

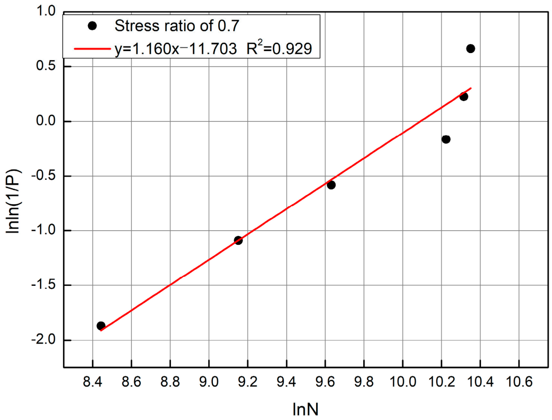
Base-to-Surface Ratio	Cement Content (%)	Stress Ratio	Fatigue Life Values						SD	COV/%
			1#	2#	3#	4#	5#	6#		
8:2	4	0.60	97,095	130,489	145,949	177,206	230,677	292,033	26,669	14.9
		0.65	17,470	34,993	38,377	57,759	71,106	74,847	8394	17.1
		0.70	4465	6265	9099	11,262	12,815	17,716	1780	17.3
		0.75	983	1422	2587	3186	3670	4794	530	19.1
		0.80	243	320	478	662	839	1027	114	19.1
	5	0.60	126,789	248,973	362,436	468,513	472,845	597,931	63,583	16.8
		0.65	35,893	68,725	74,321	92,574	115,932	115,932	11,492	13.7
		0.70	4643	9431	15,239	27,543	30,186	31,267	4273	21.7
		0.75	854	1653	3764	4971	5642	6680	854	21.7
		0.80	312	776	894	991	1123	1545	151	16.1
	6	0.60	360,646	446,615	511,095	688,262	733,906	994,362	86,109	13.8
		0.65	61,508	87,748	89,413	111,783	180,187	241,178	25,453	19.8
		0.70	14,921	18,540	22,589	28,545	32,366	42,181	3716	14.0
		0.75	3797	4242	5956	7624	8113	9382	831	12.7
		0.80	683	919	1093	1272	1695	2117	197	15.2
6:4	5	0.60	93,195	157,369	167,242	238,183	224,717	290,624	26,057	13.3
		0.65	24,191	31,923	43,586	52,725	71,603	73,830	7592	15.3
		0.70	5282	6838	11,423	15,618	15,968	20,472	2177	17.3
		0.75	1468	1585	2282	2738	3980	4123	428	15.9
		0.80	343	413	584	598	829	987	91	14.6
10:0	5	0.60	232,001	220,989	530,616	520,816	688,984	930,967	101,367	19.5
		0.65	39,815	75,565	80,040	77,894	130,942	204,822	21,755	21.4
		0.70	9223	14,508	23,229	23,134	32,324	40,851	4291	18.0
		0.75	1889	2476	3447	4309	6232	11,100	1265	25.8
		0.80	416	723	733	1173	1877	2108	255	21.8



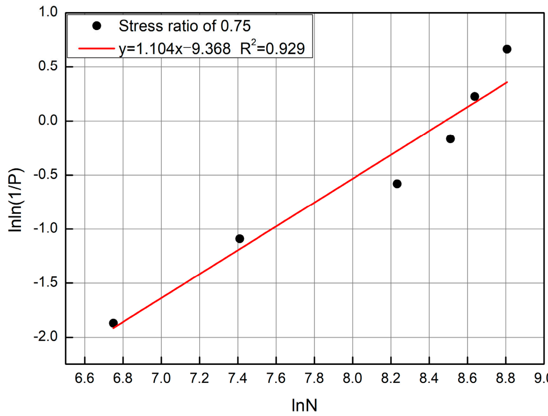
(**a**) stress ratio of 0.60



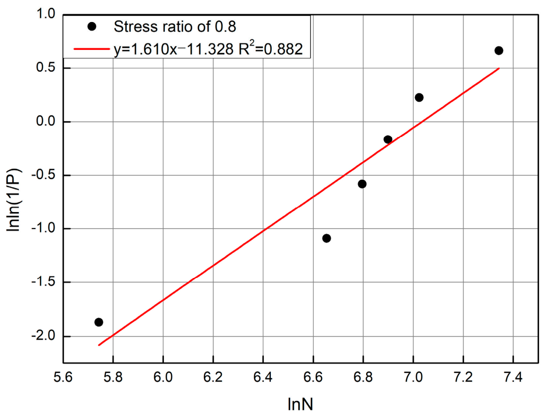
(**b**) stress ratio of 0.65



(**c**) stress ratio of 0.70



(**d**) stress ratio of 0.75



(**e**) stress ratio of 0.80

Figure 6. Weibull distribution fitting results for cold recycled mixture with 5% cement content and 8:2 base-to-surface ratio. (**a**) Stress ratio of 0.60; (**b**) stress ratio of 0.65; (**c**) stress ratio of 0.70; (**d**) stress ratio of 0.75; (**e**) stress ratio of 0.80.

3.2. Weibull Equation

Substituting the fatigue life values from Table 5 back into Equation (9) yields the Weibull distribution equations for the fatigue lives of various cold recycled mixtures at different stress ratios, as presented in Table 6. Utilizing the fitted Weibull distribution equations allows for the calculation of the fatigue life for cold recycled mixtures at any given reliability level. The above statistical analysis was conducted using the ORIGIN2018 software program. Table 7 lists the fatigue lives of all experimentally produced FDR mixtures at the stress ratios of 0.6, 0.65, 0.7, 0.75, and 0.8, with the reliability levels set at 50%, 60%, 70%, 80%, and 90%, respectively.

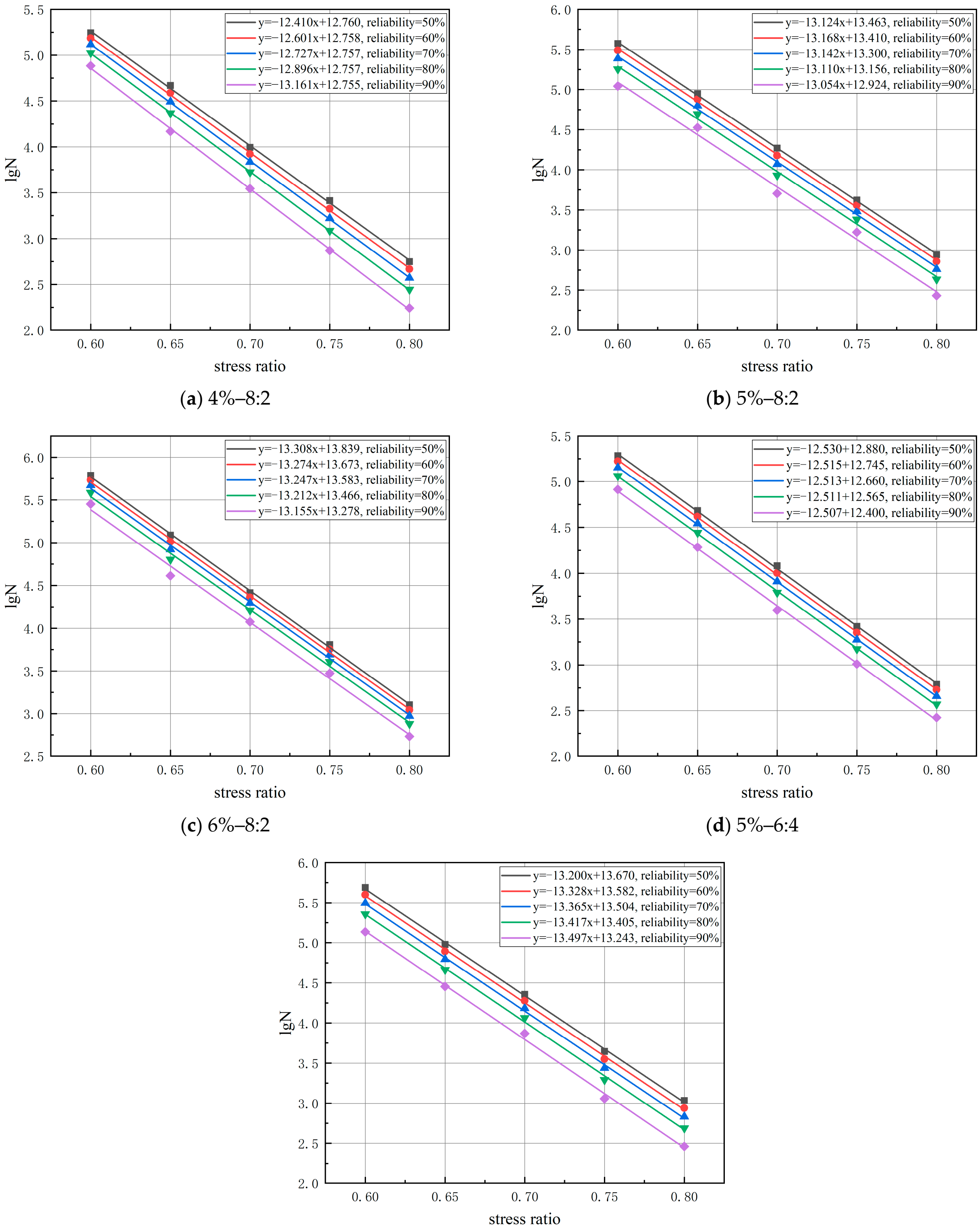
Table 6. The Weibull distribution fitting equations and R^2 for all fatigue test groups under different stress ratios.

Base-to-Surface Ratio	Cement Content	Stress Ratio	α	β	R^2
8:2	4%	0.60	2.272	27.801	0.972
		0.65	1.633	17.927	0.956
		0.70	1.829	17.180	0.992
		0.75	1.504	12.190	0.975
		0.80	1.624	10.644	0.983
	5%	0.60	1.580	20.586	0.936
		0.65	1.895	21.878	0.961
		0.70	1.160	11.703	0.929
		0.75	1.104	9.368	0.929
		0.80	1.610	11.328	0.882
	6%	0.60	2.437	32.839	0.964
		0.65	1.731	20.644	0.910
		0.70	2.391	24.684	0.983
		0.75	2.445	21.809	0.954
		0.80	2.215	16.192	0.981
6:4	5%	0.60	2.211	27.262	0.942
		0.65	2.042	22.386	0.977
		0.70	1.694	16.284	0.959
		0.75	2.007	16.162	0.931
		0.80	2.251	14.813	0.964
10:0	5%	0.60	1.477	19.718	0.881
		0.65	1.559	18.244	0.893
		0.70	1.679	17.211	0.978
		0.75	1.388	12.015	0.939
		0.80	1.433	10.375	0.950

Table 7. The expected fatigue life was calculated based on Weibull distribution equations for all fatigue test groups.

Base-to-Surface Ratio	Cement Content	Stress Ratio	Fatigue Life at Different Reliability Levels				
			50%	60%	70%	80%	90%
8:2	4%	0.60	175,202	153,180	130,782	106,391	76,467
		0.65	46,797	38,819	31,154	23,376	14,764
		0.70	9844	8331	6845	5296	3513
		0.75	2594	2117	1667	1221	741
		0.80	560	464	372	278	175
	5%	0.60	361,184	307,807	237,192	179,848	109,626
		0.65	103,272	75,933	59,940	49,567	31,495
		0.70	24,072	15,092	9898	8513	3459
		0.75	4844	3607	1904	2404	631
		0.80	1137	721	599	431	281
	6%	0.60	613,265	541,064	466,903	385,153	283,062
		0.65	122,276	102,510	83,300	63,529	41,181
		0.70	26,082	22,956	19,754	16,236	11,863
		0.75	6443	5687	4910	4052	2981
		0.80	1266	1103	938	759	541
6:4	5%	0.60	192,173	167,391	142,287	115,087	81,960
		0.65	48,285	41,580	34,872	27,715	19,190
		0.70	12,026	10,044	8125	6160	3956
		0.75	2620	2250	1882	1489	1024
		0.80	613	535	456	370	265
10:0	5%	0.60	489,591	398,191	312,230	227,286	136,749
		0.65	95,229	78,301	62,191	46,037	28,452
		0.70	22,700	18,928	15,283	11,559	7394
		0.75	4422	3549	2739	1953	1137
		0.80	1078	871	678	488	289

Following Equation (12), we conducted a linear regression utilizing the stress ratio and fatigue life data from Table 7, which yielded the curves of the fatigue equation. Figure 7 illustrates the fatigue equation curves for cold recycled mixtures with five different cement content and base-to-surface ratio combinations at five reliability levels.



(**a**) 4%–8:2 (**b**) 5%–8:2 (**c**) 6%–8:2 (**d**) 5%–6:4 (**e**) 5%–10:0

Figure 7. Fatigue equations for cold recycled mixtures with various cement contents and base-to-surface ratios under different reliability levels. (**a**) 4%–8:2; (**b**), 5%–8:2; (**c**), 6%–8:2; (**d**), 5%–6:4; (**e**), 5%–10:0.

3.3. Fatigue Equation

Using the target fatigue life at a 50% reliability level for each mixture as foundational data, a logarithmic transformation of stress levels and fatigue life values was conducted following Equation (12) for linear regression analysis. This process resulted in the fitting of stress–fatigue equations, as shown in Figure 8, and the determination of equation coefficients, as detailed in Table 8.

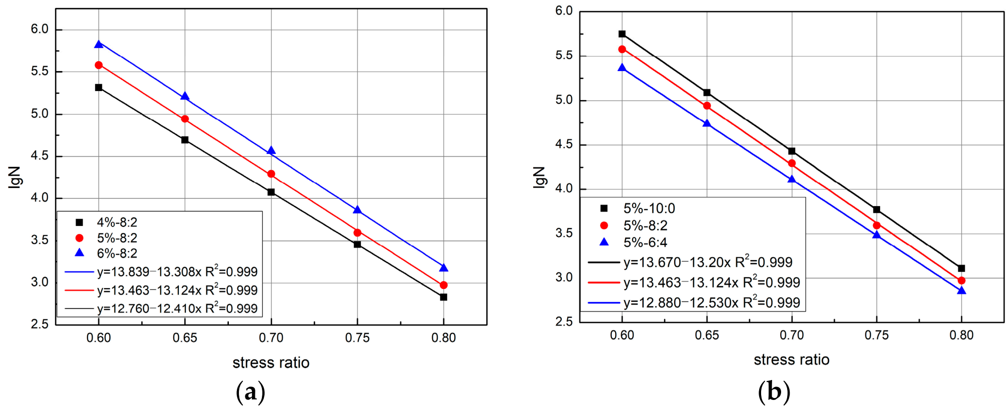


Figure 8. Comparison of fatigue equations for different cold recycled mixtures at a 50% reliability level. (**a**) Base-to-surface ratio of 8:2 and cement contents of 4%, 5%, and 6%; (**b**) 5% cement content and base-to-surface ratios of 10:0, 8:2, and 6:4.

Table 8. Fatigue equations for cold recycled mixtures with varying base-to-surface ratios and cement contents under a 50% reliability level.

Cement Content	Base-to-Surface Ratio	$\lg N = a - k\sigma/S$		
		a	k	R^2
5%	10:0	13.670	13.200	0.999
	8:2	13.463	13.124	0.999
	6:4	12.880	12.530	0.999
4%	8:2	12.760	12.410	0.999
6%	8:2	13.839	13.308	0.999
Recommended by Regulations	Inorganic-Binder-Stabilized Granular Material	13.24	12.52	/
	Inorganic-Binder-Stabilized Soil	12.18	12.79	/

As shown in Figure 8 and Table 8, with an escalation in cement contents and base-to-surface ratios, the stress–fatigue curves manifested higher positions, signifying an enhanced fatigue resistance of the mixtures. A greater a value corresponded to an elevated fatigue life limit for the cold recycled mixture, and a higher k value indicated heightened sensitivity to variations in stress levels. This phenomenon can be ascribed to the augmented cement content resulting in a larger volume of hydration products and a denser mixture. The increased contact surface between aggregates and hardened mortar amplified the fatigue performance of the base mixture. Nevertheless, it concurrently raised the stiffness of the mixture, rendering it more susceptible to variations in stress levels.

Furthermore, an increase in the RAP content led to a decrease in both the a and k values. This phenomenon can be attributed to the presence of numerous original microcracks and voids between RAP and the hardened mortar, which expedited the generation and propagation of cracks in the cold recycled mixture under cyclic loading. In contrast, RIA exhibited higher strength and, during the specimen molding process, to some extent, could hinder the development of internal microcracks, thereby decelerating the rate of fatigue cumulative damage and consequently extending the fatigue life of the cold recycled mixture.

Simultaneously, the flexible cushioning effect of RAP reduced the sensitivity of the cold recycled mixture to stress.

We compared the fatigue equation parameters of cold recycled mixtures with the recommended fatigue failure model parameters for inorganic-binder-stabilized layers in the current Chinese specifications for the design of highway asphalt pavement. When we did sp, it was evident that, in terms of fatigue performance, the mixture with a 4% cement content, as well as the one with a 5% cement content and a low base-to-surface ratio, met the requirements for inorganic-binder-stabilized soil. Additionally, the mixture with a 5% cement content and a high base-to-surface ratio, along with the one with a 6% cement content, satisfied the requirements for inorganic-binder-stabilized granular materials.

4. Conclusions

In this study, we explored the fatigue performance of FDR-PC. Small-sample fatigue tests were conducted on FDR-PC cold recycled mixtures produced using the heavy compaction method, and a fatigue equation following the Weibull distribution was formulated. The research results lead us to draw the following conclusions:

(1) The fatigue life of cement-stabilized cold recycled mixtures adheres to a Weibull distribution, with correlation coefficients R^2 consistently surpassing 0.88.
(2) As the cement content and base-to-surface ratio increase, the fatigue life of the mixture extends, though with an associated increase in stress sensitivity.
(3) Comparisons with the fatigue equation model parameters for inorganic-binder-stabilized layers in the Chinese specifications for the design of highway asphalt pavement reveal that the mixture with a 4% cement content, and that with a 5% cement content and a low base-to-surface ratio, meet the criteria for inorganic-binder-stabilized soil. Furthermore, the mixture with a 5% cement content and a high base-to-surface ratio, along with that with a 6% cement content, satisfy the specifications for inorganic-binder-stabilized granular materials.

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