Research Article

Compressive Toughness Loss Rate and Softening Characteristic Analysis of Pasture Fiber-Rubber Powder Concrete

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To develop the utilization of pasture fibers and waste tire rubber powder, the effect of different blending levels of modified pasture fibers (2 kg/m³, 3 kg/m³, and 4 kg/m³) on the loss rate of compressive toughness and softening characteristics of rubber powder concrete was studied. In addition, RapidAir457 system imaging analysis and microscopic electron microscope photo analysis were carried out to analyze the distribution pattern of modified pasture fibers and rubber powder in concrete. The results show that the peak load of concrete is higher than other pasture fiber dosing test groups when 3 kg/m³ is incorporated in 20 mesh and 60 mesh rubber powder. With the increase of pasture fiber content, the compressive toughness loss of MC60 group and MC80 group increased first and then decreased. The softening curve analysis showed that MC-3 was more capable of absorbing damage energy in the strain range of 0.0005–0.0009 than the MC-2 group. According to the RapidAir457 system imaging analysis, the pasture fibers form a web-like organization inside the concrete when the pasture fiber is mixed at 3 kg/m³.

1. Introduction

More than 20 billion car tires are scrapped worldwide annually and the most common disposal approach for end-of-life tires is to bury them [1]. Such methods not only pollute the environment but also endanger human health. If waste tire rubber powder is added to the concrete as an admixture, it can both change certain properties of the concrete and recycle the waste tire rubber powder. Rubber concrete has a lower density, higher impact resistance, and better impermeability than traditional concrete [2]. For these reasons, the study of rubber concrete has become a popular research direction in recent years. As the main load-bearing material for building structures, the mechanical properties of concrete and its durability in complex environments are important. Many researchers have conducted extensive research in these two areas.

Amiri et al. [3] used micronized rubber powder (MRP) as an equal mass replacement for cement and tested the tensile properties of slag concrete. It was found that the tensile strength of slag concrete decreased by 7% and 17.6% when MRP was replaced at 2.5% and 5%, respectively. Kumar and Dev [4] used H₂SO₄-modified rubber powder to replace sand with equal mass and found that the compressive strength of concrete decreased by 20.36% when the modified rubber powder was replaced at 15%. It was attributed to the incompatibility of the rubber powder with the stiffness of the cement paste material. Zhang et al. [5] found that the concrete shear stress decreased by 30.6% when 30% of the sand dosage was replaced by an equal volume of rubber powder. The reason for this is that the rubber powder weakens the shear surface of the concrete, resulting in a reduction in concrete shear stress. Di et al. [6] used uniaxial compression tests on cylinders to calculate the elastic strain energy release ratio of rubber powder concrete to characterize the toughness of rubber powder concrete. He found that the incorporation of rubber powder reduced the brittleness of the concrete and improved its toughness. Abdullah et al. [7] incorporated rubber powder as an additive into foam concrete and found that the compressive strength decreased significantly when the rubber powder was incorporated at a rate of more than 9%. An important reason
for the reduction in the mechanical properties of concrete is that the incorporation of rubber powder introduces a large number of air bubbles and increases the number of initial interfacial defects [8].

Although the incorporation of rubber powder will reduce the compressive and shear properties of concrete, the durability performance of rubber powder concrete in complex environments is excellent. Under freeze-thaw cycle conditions, the surface of rubber powder concrete was flat and angular after 30 freeze-thaw cycles compared with ordinary concrete, and the surface of rubber powder concrete began to flake off after 60 freeze-thaw cycles [9]. It was because the rubber particles distributed in the concrete had a strong deformation capacity, which provided a good buffer for the ice expansion and can to some extent inhibit the development and expansion of cracks under freeze-thaw cycles [10]. In the –30°C environment, the loss rate of rubber powder concrete ductility index is lower than that of ordinary concrete and the rubber powder enhances the ductility of concrete in a low-temperature environment [11]. In the 60°C environment, plastic deformation is mainly caused by pores and cracks in the cement matrix due to the sound elasticity of the rubber particles [12]. In a Cl-erosion environment, rubber concrete with rubber powder particle size of 3–6 mm and 5% admixture has a denser internal structure than normal concrete, due to the addition of rubber powder improving the microcrack structure of rubber concrete [13, 14].

The above studies illustrate that although rubber powder concrete is not as compressive as ordinary concrete, it is more durable than ordinary concrete in complex environments. Some scholars have attempted to improve the compressive performance of rubber powder concrete by surface modification. Through tests, it was found that the compressive and flexural strengths of rubber powder concrete were much lower than those of ordinary concrete, whether the rubber powder was surface-modified or not [15]. Therefore, the incorporation of fibers into rubber powder concrete was considered to enhance the mechanical properties. It has been shown that the incorporation of industrial fibers can enhance the mechanical properties of engineering cement composites. For example, Huang et al. [16] blended polyethylene fibers with steel fibers into engineered cement composites to improve their compressive strength. Xu et al. [17, 18] found that engineered cement composites with polyethylene fibers of 24 μm diameter and 18 mm length exhibited good ductility. At the same time, the fibers bonded very strongly to the matrix which helps to withstand the loads. Researchers have tried incorporating industrial fibers into rubber powder concrete and found that the mechanical properties of the rubber powder concrete were improved. For example, when the polypropylene fiber content was increased from 1.2% to 1.5%, the compressive strength of the rubber powder concrete increased by 6.5% [19].

However, the production of industrial fibers consumes considerable industrial resources which are costly and cause pollution to the natural environment. If plant fibers could replace industrial fibers and be used in concrete materials, the previous scenario would be alleviated. Natural fibers have advantages in terms of environmental, energy, economic, and resource conservation [20]. For example, natural fibers can be obtained from the stems, bark, leaves, and pulp of plants [21]. Such fibers are easily accessible and do not require much of a process [22]. The cost of extracting natural fibers in such a way is low, which is one of the important advantages of natural fibers [23].

Recently, several projects have been undertaken to increase the value of organic fibers as an alternative to industrial fibers [24]. For example, by adding sisal fiber to concrete, the concrete slump showed greater fluidity [25]. In addition, the flexural strength and fatigue life of concrete increased with increasing sisal hemp fiber content if the amount of sisal hemp fiber incorporated was less than 0.15% [26]. Many types of plant fibers are used in the manufacture of construction materials, such as wheat straw fibers [27], coir fibers [28], wood fibers [29], and alfa plant fibers [30]. Mixing wood fiber at a dosage of 0.4% into concrete containing 1.0% rubber powder will increase the compressive strength by 1.09 times [29]. The tensile strength of rubber powder concrete prepared by mixing rubber powder with corn straw cellulose was enhanced because the corn straw fibers in the corn straw cellulose acted as a reinforcement to the tensile strength [31]. The incorporation of pine shavings into rubber powder concrete enhances the toughness of rubber powder concrete while decreasing the maximum modulus of elasticity of concrete by 59% [32]. The above scholars’ studies provide some research basis for using plant fibers to improve the performance of rubber powder concrete.

China is rich in grassland resources, especially in the Inner Mongolia Autonomous Region, where there are large areas of natural grassland. However, most pasture grasses wither and degrade naturally in the grasslands and only a small amount is used as animal feed. Therefore, it has become an urgent task for Chinese researchers to accelerate the integrated use of China’s pasture resources and replace high-cost industrial fibers with cheap pasture fiber resources. Pasture grass grows all year round, but pasture fiber is rarely used as a construction material. If pasture fibers are used in concrete, it will provide a new avenue for exploiting pasture resources. In the test, unmodified rubber powder was selected as the concrete admixture, so that the mechanical properties of the concrete could be obtained with the rubber powder in its original performance. The pasture fibers were dealt with a modified method, as described in Section 2.2. By incorporating different amounts of modified pasture fibers into the rubber powder concrete, the effect of modified pasture fibers on the compressive toughness properties of rubber powder concrete was investigated to accumulate scientific data for the combined use of these two materials.

2. Experimental Procedure

2.1. Materials. Cement was made of ordinary silicate cement of grade 42.5, whose properties meet GB 175-2007 [33]. The sand was made of well-graded medium sand. The coarse aggregate was made of ordinary pebbles with a particle size...
range of 5–15 mm and the properties of the sand and pebbles were by GB 175-2007 [34]. FDN-C naphthalene water reducing agent with a water reduction rate of 20% was used. The water source was tap water. The plant fiber was obtained from the *Leymus chinensis* plant pasture in the Inner Mongolia Autonomous Region. The length of the intercepted pasture fiber was 20 mm (diameter is 0.4 mm) and the practical photo was shown in Figure 1.

Rubber powder was 20 mesh, 60 mesh, and 80 mesh and relevant physical and chemical properties were shown in Figure 2 and Table 1. To maintain the original properties of the rubber powder, no modification of the rubber powder is carried out. The relevant properties of the rubber powder satisfy JT/T 797-2019 [35].

2.2. Modified Pasture Fiber. The fibers will lose their ductile properties and their role in absorbing destructive energy, if they are overlong. The study demonstrated that the compressive strength of concrete increased when the mixed sisal fibers possessed a length/diameter ratio of 50 [36]. Moreover, the flexural toughness of 2% bamboo fiber (aspect ratio: 50) concrete is 200% higher than that of ordinary matrix [37]. Based on the above studies, the length of the intercepted pasture fiber is 20 mm (diameter is 0.4 mm), and the length/diameter ratio is controlled at 50.

The smooth surface of the pasture fiber is not conducive to bonding with the cement mortar. Researchers used a 3% NaOH solution to modify the surface of jute and straw fibers [38]. The modification steps are as follows: (1) the fibers were first soaked in NaOH solution for 4 h and further soaked in water for 10 h. (2) The fibers were then rinsed with water 5–7 times to drain the fibers from impurities until the rinse water became clear. (3) The fibers were then placed in an electric drying oven at 85 ± 1°C for 24–30 h, cooled to room temperature, packed in sealed plastic bags, and set aside. The method was adopted in this study to modify the pasture fiber. According to the method, it was found that the mass of the modified pasture fibers reached a constant weight after 30 h of drying in a drying oven. At this point, a small amount of the modified pasture fiber in the constant weight state was removed and continued to dry for 30 h, and the mass was found to be unchanged. Therefore, the modified pasture fiber obtained according to the above modification method is considered to be in a dry state. The modified pasture fiber in this state was used directly in the test. Alkalization of natural fibers leads to the fibrillation effect, which is splitting of a single-fiber bundle into smaller ones, increasing the effective area for mechanical interlocking between fibers and matrix, thus leading to improve inter-facial bonding [39]. The modified fiber is shown in Figure 3.

As can be seen from Figure 3, the SEM images of the pasture fiber before and after modification have an accuracy of 200 μm. The SEM images show that the surface of the pasture fiber before modification is smooth with a gelatinous layer on the surface with visible plant stomata. The surface of the modified pasture fiber is rough and uneven, with filamentous surface fibers, thereby increasing the ability of the fiber to bind to the cement paste. We can also see from Figure 3 that the tensile damage morphology of the pasture fiber and the micro-physical state of the rubber powder have an accuracy of 200 μm. It can be inferred that the pasture fiber was subjected to tensile damage in absorbing the damage energy, while the rubber powder was embedded in the concrete in a granular state.

Pasture is a major source of animal feed rich in fiber and pectin. It has been shown that pectin can trap Ca\(^{2+}\) ions in the polymer structure [40]. Table 2 lists the mass ratios of the elements in the pasture fiber based on energy spectrum analysis experiments. It can be inferred from Table 2 that the Ca element was reduced by 95.03% and the proportions of Na, Al, Si, and O were greatly reduced after modification, indicating that a significant amount of pectin was removed from pasture fiber.

2.3. Experimental Design

2.3.1. Experimental Design of Mechanical Property. The concrete without rubber powder and modified pasture fiber was used as a reference group (I2), with a design strength grade of C40. The test group with only modified pasture fiber was named MC, with modified pasture fiber content of 2 kg/m\(^3\), 3 kg/m\(^3\), and 4 kg/m\(^3\), respectively. The three groups of concrete with a particle size of 20 mesh, 60 mesh, and 80 mesh (rubber powder at 3% of the mass of the cement) were named MC20, MC60, and MC80, respectively. The mixture proportion of the control group was designed following JGJ 55-2011 [41]. The material composition of concrete is provided in Table 3.

Some researchers have used concrete cubic blocks for testing stress-strain curves. Yu et al. [42] used a 100 mm × 100 mm × 100 mm concrete cube to collect displacement-load data through uniaxial compression tests (data collection was carried out through the own acquisition system of the press) and then obtained stress-strain curves. Chen et al. [43] used a standard concrete cube of 150 mm × 150 mm × 150 mm to collect load-displacement data by uniaxial compression testing and then calculated the stress-strain curves. The load-displacement data were collected using an electrohydraulic servo press with its own acquisition system. Chen et al. [43] calculated the stress and strain by using equations (1) and (2), where \(N\) is the load, \(A\) is the compressive area, \(\Delta l\) is the compressive deformation value, and \(l\) is the height of the cube. Stress-strain data for concrete can be obtained directly by mounting the AE instrument and AE monitor on the outside of the press. Cui et al. [44] adopted that test method and used a 100 mm × 100 mm × 100 mm concrete cube to obtain stress-strain data. In combination with the above research methods [42–44], a 100 mm × 100 mm × 100 mm concrete cube was selected for this test to obtain displacement-load data by uniaxial compression testing, which in turn was used to calculate the stress-strain curve. The displacement-load data acquisition equipment is shown in Figure 4. The equipment consists mainly of built-in displacement measurement equipment.
Figure 1: The practical photo of pasture fiber.

Figure 2: Relevant physical and chemical properties of rubber powder. (a) The micrograph of rubber powder. (b) The elemental energy spectrum curve.

Table 1: Main physical indexes of rubber powder.

| Properties     | Residue on sieve (%) | Iron content (%) | Carbon black content (%) | Rubber hydrocarbon content (%) | Water content (%) |
|----------------|----------------------|------------------|--------------------------|-------------------------------|-------------------|
| Result         | 9.6                  | 0.027            | 29                       | 52                            | 0.82              |
system, electrohydraulic servo pressure system, and displacement-load recording software system. Three cubes were tested in each test group and the displacement-load data for the cubes with the smallest values of |\( f_c - f_{c0} \)| and |\( \Delta I - \Delta I_0 \)| were selected to calculate the stress and strain. \( f_c \) is the peak load, \( \Delta I \) is the displacement at the peak load, \( f_{c0} \) is the average peak load, and \( \Delta I_0 \) is the average displacement at the peak load.

\[
\sigma = \frac{N}{A}, \quad (1)
\]

\[
\varepsilon = \frac{\Delta I}{I}. \quad (2)
\]

A 100 mm × 100 mm × 100 mm nonstandard cube was used for the test. According to GB/T 50081-2019 [45], as the
100 mm × 100 mm × 100 mm cube is a nonstandard cube, the stress should be calculated by multiplying the conversion factor (0.95), i.e., equation (3). The stress-strain curve can be calculated from equations (2) and (3).

\[ \sigma = \frac{N}{A} \times 0.95. \quad (3) \]

2.3.2. Morphology and Distribution of Pasture Fibre and Rubber Powder. To study the morphology and distribution of pasture fiber in the cut surface of test concrete groups, RapidAir457 stomatal structure analyzer was used for imaging analysis. The sample to be tested with the RapidAir457 needs to be a specially made square octagonal sample. Experimental samples of RapidAir457 were shown in Figure 5.

The steps of making samples: firstly, we used a cutting machine to cut the concrete cube test block into a square test piece with a thickness of 15 mm. Then, we cut off the corners of the square lamina sample and made it into a regular octagonal specimen. Furthermore, we polished the surface of the regular octagonal specimen, and then smeared the polished sample surface with black ink and waited for it to dry. Finally, the prepared nano CaCO₃ paste was applied to the surface of the sample and gently pressed. The excess paste was scraped off with a knife. To further study the microstructure of rubber powder and pasture fiber in concrete, we used scanning electron microscopy for imaging analysis.

3. Results and Analysis

3.1. Stress-Strain Curve. According to the different mesh numbers of rubber powder, the experimental groups were divided into four groups: MC group (only mixed pasture fiber), MC20 group (mixed 20 mesh rubber powder), MC60 group (mixed 60 mesh rubber powder), and MC80 group (mixed 80 mesh rubber powder). The stress-strain curves of these four groups were shown in Figure 6. It can be seen from Figure 6 that the strains at the peak stresses in the test groups with modified pasture fiber alone, with both modified pasture fiber and rubber powder are greater than those in the reference group (JZ). The peak stress in the test group with 60 mesh rubber powder mixed with modified pasture fiber was much greater than in the JZ group. Moreover, the slope of the rising section of the stress-strain curve is lower in the group with modified pasture fiber and rubber powder than in the reference group (JZ). These findings indicate that
the incorporation of modified pasture fiber and rubber powder can absorb the damage energy through the deformation of the rubber powder itself and the tensile fracture of the pasture fiber, thereby enhancing the deformation performance of the concrete. The slope of the rising section of the stress-strain curve of the test group with modified pasture fiber and rubber powder is lower than that of the reference group because of the incorporation of these two materials, which lack stiffness and impact the overall stiffness of the concrete material.

From Figure 6, the peak load of the rubber powder concrete test with 3 kg/m^3 of pasture fiber is higher than other mixed amount pasture fiber test groups. As the internal network structure is more conducive to limiting the development of internal damage before peak load and delaying plastic failure when the mixed amount of pasture fiber is 3 kg/m^3. As can be seen from the stress-strain curves of the MC80 group, the strain curves of the MC80-2 and MC80-3 groups drop abruptly when the peak load is reached, resulting in a sharp angle in the strain curve at the peak load. It indicates that the damage to the internal structure of the concrete composed of 80 mesh rubber powder and modified pasture fibers (2 kg/m^3 and 3 kg/m^3) has an abrupt nature when the peak load is reached. At this time, the internal structure deformation capacity is weak and its strength is low, showing obvious brittle damage. Meanwhile, the concrete prepared by combining 80 mesh rubber powder with 4 kg/m^3 modified pasture fiber had the lowest peak load. Therefore, the MC80 group was the worst test group in terms of mechanical properties.

As can be seen from the stress-strain curves of MC group, MC20 group, and MC60 group that the stress value of MC-3 is higher than that of other test groups before the strain is...
1.2 \times 10^{-3}$, and the stress value of MC20-2 is higher than that of other test groups before the strain is $1.6 \times 10^{-3}$. The MC60-4 test group has the same result before the strain is $1.2 \times 10^{-3}$. This indicates the MC-3, MC20-2, and MC60-4 groups were able to maintain their maximum capacity to absorb damage energy in the interval from 0 to a certain strain value.

As can be seen from Figure 6, the rising section of the stress-strain curve tends to rise more slowly when each test group is initially loaded, and the stress-strain curve shows a linear increase as the load increases. The gentle curve at the initial loading of the test group mixed with rubber powder and modified pasture fiber were all on the lower side of the JZ group. The concrete loading phase was divided into three main stages: the compaction stage, the near-elastic stage, and the crack evolution stage [46]. During the compaction stage, the stresses remain at a low value and grow very slowly with increasing strain. During the compaction stage, the pores are in the process of being compacted and closed. As the pores are gradually compacted, the specimens are uniformly compressed and the stress-strain curve increases approximately linearly, indicating the near-elastic stage [12]. During the compaction stage, the curve for the test group incorporating rubber powder with modified pasture fiber was on the lower side of the JZ, indicating that the incorporation of rubber powder with modified pasture fiber resulted in the formation of more internal pores and cracks within the concrete. The presence of the compaction stage does not affect the subsequent calculation of the ideal stiffness, as the ideal stiffness can be considered as the tangential modulus of elasticity within a certain strain interval within the elastic stage.

3.2. Compressive Toughness Loss Rate

3.2.1. Compressive Toughness and the Ideal Stiffness. Fracture toughness is the ability to characterize the ability of a material to stop crack extension, and the fracture toughness properties of concrete have been investigated using three-point loading tests on notched beams [47–49]. Concrete compressive toughness is an important indicator for analyzing the energy dissipation capacity of a material and is related to the area under the uniaxial compressive stress-strain curve of concrete [50]. Many scholars have used the area under the uniaxial compressive stress-strain curve of concrete to characterize compressive toughness. Noaman et al. [51] adopted the area under the stress-strain curve measured in concrete compressive tests to characterize compressive toughness. Li et al. [52] stated that compressive toughness can be calculated as energy absorption, i.e., the area under the stress-strain curve. Li et al. [52] used the sum of the area under three parts of the stress-strain curve to characterize compressive toughness: the area of the rising section of the stress-strain curve, the area of the peak stress section of the stress-strain curve, and the area of the falling section of the curve when the peak stress has dropped by 10%. In this test, the area under the stress-strain curve in the region where the stress reaches the peak stress from 0 is used to characterize the compressive toughness and is calculated as follows:

\[ W = \int_{0}^{\varepsilon_0} \varepsilon \cdot \delta \varepsilon. \]  

In the above equation, \( W \) is the area under the stress-strain curve, i.e., failure energy density (unit: MJ/m$^3$). \( \varepsilon_0 \) indicates the strain value corresponding to the peak stress. The deformation before the peak stress is dominated by elastic-plastic deformation. In the rising section of the stress-strain curve, there is always an interval with a large slope over a considerable strain range, whereby the curve increases almost linearly. This section of the curve is defined as the ideal curve. The stiffness (slope) of the curve is the ideal stiffness \( E^* \), which differs between each test group. With the increase of load, the extent of internal damage sustained by the concrete becomes bad. Therefore, its ability to resist the load continues to weaken, as evidenced by the gradual decrease in the slope of the stress-strain curve around the peak stress. Assuming that the initial stiffness of the stress-strain curve is the ideal stiffness \( E^* \) (i.e., the slope of the stress-strain curve is \( E^* \)), when the strain is small, the stress-strain curve at this point is higher than the actual curve. Thus, the curve with the slope of \( E^* \) is defined as the theoretical curve.

As inferred from equation (4), the failure energy density absorbed under the theoretical curve (defined as \( W_0 \)) is greater than the failure energy density absorbed under the actual curve (defined as \( W_e \)). The area under the stress-strain curve is proportional to the failure energy density. Therefore, the difference between \( W_0 \) and \( W_e \) is the difference in compressive toughness between the ideal and actual states, defined as the compressive toughness loss: \( W_{\text{loss}} \). Divide \( W_0 \) into the toughness loss \( W_{\text{loss}} \), the result is the compressive toughness loss rate (T) which is shown in equation (5). The smaller the compressive toughness loss rate of the specimen, the higher the compressive toughness. The calculation of the stress-strain curve equations under ideal stiffness is necessary to calculate \( W_0 \):

\[ T = \frac{W_e - W_0}{W_0} = \frac{W_{\text{loss}}}{W_0}. \]  

3.2.2. Stress-Strain Relationship Based on the Ideal Stiffness. With the increasing load, the internal damage of the concrete continues to increase and the load carrying capacity continues to weaken. In damage mechanics theory, the change of effective bearing area caused by the damage is described, and the relationship between nominal and effective stress is given as follows [53]:

\[ \sigma = \frac{F}{A}, \]  

\[ \sigma^* = \frac{F}{A^*}, \]  

\[ \sigma = \left( \frac{A^*}{A} \right) \sigma^*. \]
In equations (6)–(8), $F$ denotes the load, $N$; $\sigma$ and $\sigma^*$ are nominal stress and effective stress, respectively, MPa; $A$ and $A^*$ are the nominal bearing area and effective bearing area, mm$^2$. For concrete materials, the damage variable usually characterizes the development of internal damages. The damage variable is generally defined as the ratio of damage area in concrete to the total bearing area (nominal bearing area) [54]:

$$D = \frac{A - A^*}{A} = 1 - \frac{A^*}{A}. \quad (9)$$

The ideal stiffness ($E^*$) of concrete after initial damage is used as the initial state, which is equivalent to the nondestructive state of concrete in damage mechanics, $E^* = E$. As the pasture fiber and rubber powder are nonconstruction materials, their participation is not compatible with the concrete material and will lead to damage. It can be inferred from Figure 6 that the peak load of test groups with pasture fiber and rubber powder is lower than that of the reference material. Like a rock, the strength distribution of concrete can be described by the Weibull distribution [55]. It is assumed that the basic parameters (i.e., $N$, $N^*$, stress: $\sigma$, strain: $\varepsilon$, and damage variable: $D$) of the material follows the Weibull distribution. Thus,

$$N^* = N \cdot \int_0^{\varepsilon_0} p(\varepsilon) d\varepsilon. \quad (15)$$

In equation (15), $p(\varepsilon)$ follows Weibull’s distribution law and the uniaxial damage evolution equation is (16) to (18).

$$D = \frac{A - A^*}{A} = \frac{N^*}{N} = \frac{\int_0^{\varepsilon} p(\varepsilon) d\varepsilon}{\int_0^{\varepsilon_0} p(\varepsilon) d\varepsilon}, \quad (16)$$

$$D = \int_0^{\varepsilon} p(\varepsilon) d\varepsilon = \int_0^{\varepsilon} k \frac{(\varepsilon/\lambda)^{k-1}}{\Gamma(k)} \cdot \exp \left[-\left(\frac{\varepsilon}{\lambda}\right)^k\right], \quad (17)$$

$$D = 1 - \exp \left[-\left(\frac{\varepsilon}{\lambda}\right)^k\right] \cdot \frac{\lambda}{k}. \quad (18)$$

where $\lambda$ and $k$ are the calculated parameters, and $\varepsilon$ denotes the strain. Combining equation (14) with equation (18) yields the uniaxial damage stress-strain curve relationship: equation (19). The boundary conditions for the uniaxial damage stress-strain curve relationship are: (1) the strain is 0 when the stress is 0; (2) the slope of the stress-strain curve at 0 strain is $E^*$; (3) the strain corresponding to the peak stress is $\varepsilon_0$; and (4) the slope of the stress-strain curve at the peak stress is 0. Therefore, we took the derivative of equation (19) and equation (20).

$$\sigma = E^* \cdot \varepsilon \cdot \exp \left[-\left(\frac{\varepsilon}{\lambda}\right)^k\right]. \quad (19)$$

$$\frac{d\sigma}{d\varepsilon} = E^* \cdot \exp \left[-\left(\frac{\varepsilon}{\lambda}\right)^k\right] \cdot \frac{1 - k \left(\frac{\varepsilon}{\lambda}\right)^k}{\left(\frac{\varepsilon}{\lambda}\right)^k}. \quad (20)$$

Equations (21) to (23) were obtained based on equation (20) and condition (4).

$$\frac{d\sigma}{d\varepsilon} = E^* \cdot \exp \left[-\left(\frac{\varepsilon_0}{\lambda}\right)^k\right] \cdot \left[1 - k \left(\frac{\varepsilon}{\lambda}\right)^k\right] = 0, \quad (21)$$

$$1 - k \left(\frac{\varepsilon_0}{\lambda}\right)^k = 0, \quad (22)$$

$$\lambda = \frac{\varepsilon_0}{(1/k)^{1/k}}. \quad (23)$$

Equation (24) was obtained based on equation (23), equation (19), and condition (3).

$$k = \frac{1}{\ln \left(E^*/\sigma_0/\varepsilon_0\right)}. \quad (24)$$

In the equations above, the ideal stiffness is $E^*$, the peak stress is $\sigma_0$, $k$ and $\lambda$ are the calculation parameters and the calculated values of the above equations are shown in Table 4. Stress-strain curve relationships are shown in Figure 7.
# Table 4: Calculation data.

| Test group | $\sigma$ | $\sigma_0$ (MPa) | $\varepsilon_0$ | $E^*$ (MPa) | $\lambda$ | $k$ |
|------------|----------|-----------------|----------------|-------------|-----------|-----|
| JZ         | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00183)^{1.96367}]$ | 42.25125 | 0.0013 | 54083 | 0.00183 | 1.96367 |
| MC-2       | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00217)^{1.65935}]$ | 34.49260 | 0.0016 | 39385 | 0.00217 | 1.65935 |
| MC-3       | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00281)^{1.92018}]$ | 36.07340 | 0.0020 | 30362 | 0.00281 | 1.92018 |
| MC-4       | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00284)^{2.08370}]$ | 32.80445 | 0.0020 | 26505 | 0.00284 | 2.08370 |
| MC20-2     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00246)^{1.70415}]$ | 32.84530 | 0.0018 | 32813 | 0.00246 | 1.70415 |
| MC20-3     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00254)^{1.97968}]$ | 36.40400 | 0.0018 | 33516 | 0.00254 | 1.97968 |
| MC20-4     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00248)^{2.08370}]$ | 32.26200 | 0.0018 | 31825 | 0.00248 | 2.08370 |
| MC60-2     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00303)^{1.19995}]$ | 29.40155 | 0.0026 | 26021 | 0.00303 | 1.19995 |
| MC60-3     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00231)^{2.56448}]$ | 33.61955 | 0.0024 | 31521 | 0.00231 | 2.56448 |
| MC60-4     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00284)^{1.23302}]$ | 31.70625 | 0.0014 | 35929 | 0.00284 | 1.23302 |
| MC80-2     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00173)^{3.13000}]$ | 26.26370 | 0.0012 | 30125 | 0.00173 | 3.13000 |
| MC80-3     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00200)^{2.16683}]$ | 31.70625 | 0.0014 | 35929 | 0.00200 | 2.16683 |
| MC80-4     | $\sigma = E^* \cdot \exp[-(\varepsilon/0.00205)^{1.41954}]$ | 25.23390 | 0.0016 | 31901 | 0.00205 | 1.41954 |

Figure 7: Stress-strain curve relationships under ideal stiffness. (a) Stress-strain curve relationship of MC group. (b) Stress-strain curve relationship of MC20 group. (c) Stress-strain curve relationship of MC60 group. (d) Stress-strain curve relationship of MC80 group.
3.2.4. Analysis of Compressive Toughness Loss Rate.

Equation (25) is obtained from equations (4) to (5), $A_1 = \int_0^{\varepsilon_0} u(\varepsilon)d\varepsilon$ is the area of theoretical stress-strain curve (i.e., the uniaxial damage stress-strain curve relationship before peak loading). $A_2 = \int_0^{\varepsilon_0} \nu(\varepsilon)d\varepsilon$ is the area of the actual stress-strain curve before peak loading. $A_1$ and $A_2$ can represent the amount of the absorbed damage energy. The calculated values were listed in Table 5.

$$T = \frac{W_{\text{loss}}}{W_0} = \frac{W_0 - W_g}{W_0} = \frac{\int_0^{\varepsilon_0} u(\varepsilon)d\varepsilon - \int_0^{\varepsilon_0} \nu(\varepsilon)d\varepsilon}{\int_0^{\varepsilon_0} u(\varepsilon)d\varepsilon} = \frac{A_1 - A_2}{A_1}. \tag{25}$$

The smaller the compressive toughness loss rate ($T$) is, the higher the utilization effect of compressive toughness the test group will get. Therefore, it can be inferred from Table 5 that the compressive toughness loss rate ($T$) of MC60 groups and MC80 groups increased at first and then decreased, indicating that the compressive toughness of these two groups decreased and then increased with the increase of the amount of pasture fiber content from $2$ kg/m$^3$ to $4$ kg/m$^3$. In other words, the incorporation of $2$ kg/m$^3$ and $4$ kg/m$^3$ modified pasture fibers in 60 mesh and 80 mesh rubber powder concrete can better improve the compressive toughness of the concrete. In the MC20 group, $T$ tends to become progressively larger with the increase of modified pasture fibers. The MC20-2 group showed the lowest loss of compressive toughness compared with the other test groups. It indicates that the combination of 20 mesh rubber powder at $3\%$ and modified pasture fiber at $2$ kg/m$^3$ resulted in the highest compressive toughness utilization of the concrete. In the MC group, $T$ tends to decrease and then increase with the increase of modified pasture fibers. It indicates that when only modified pasture fibers are incorporated, the compressive toughness tends to increase and then decrease as the amount of modified pasture fibers increases.

3.3. Softening Curves Analysis. There are a number of materials, such as rock, concrete, and dense soils, which when compressed at a constant axial strain rate under conditions of either uniaxial stress or triaxial compression exhibit a phenomenon called “strain softening” [56]. The strain softening can be interpreted as follows: the further deformation requires less stress than the original stress after $1$ or more loading and unloading of the material specimen. That is to say, the material has become soft. The test group with the best compressive toughness does not mean that this group has a strong ability to absorb damage energy in the arbitrary section of the curve before $\varepsilon_0$. To compare the magnitude of the damage energy absorbed by the material at the same strain of the actual stress-strain curve, we calculated $V$ under the same strain ($\varepsilon_1$) to study.

$$V = \int_0^{\varepsilon_1} \varepsilon \cdot d\varepsilon. \tag{26}$$

$\varepsilon_1$ is the smallest $\varepsilon_0$ in each type of test group. $\varepsilon_0$ is the strain value at peak load. The $\varepsilon_0$ values of the four types of test groups are as follows: MC is $1.6 \times 10^{-3}$, MC20 is $1.8 \times 10^{-3}$, MC60 is $1.6 \times 10^{-3}$, and MC80 is $1.2 \times 10^{-3}$. The values of $V$ were listed in Table 5. Based on the $V$ of Table 5, we can obtain the test groups with the maximum absorption failure energy at $\varepsilon_1$ from the four types of groups (MC, MC20, MC60, and MC80), which are defined as the optimal groups. In each type of experimental group, the other test groups can be seen as being obtained from the optimal test group after softening. The softening relationship between the optimal test group and the other test groups in the same type of experimental group is as follows:

$$g(\varepsilon) = f(\varepsilon) \cdot K(\varepsilon), \tag{27}$$

where $f(\varepsilon)$ is the stress of the actual stress-strain curve of the optimal group and $g(\varepsilon)$ is the stress of the actual stress-strain curve of the other test group in the same category. $K(\varepsilon)$ is the softening coefficient, which is a function of strain. $K(\varepsilon)$ can be expressed as:

$$K(\varepsilon) = \frac{g(\varepsilon)}{f(\varepsilon)} \neq 0. \tag{28}$$

From Table 5, MC-2, MC20-2, MC60-4, and MC80-2 absorbed the largest fracture energy before strain $\varepsilon_1$ of the four types groups (MC, MC20, MC60, and MC80). Therefore, these four groups were selected as the optimal groups. For example, the stress values before $\varepsilon_1$ in group MC-3 can be seen as obtained by softening the stress values in group MC-2. The direction of softening has been listed in Table 6 and the softening curves are shown in Figure 8.

The magnitude of $K(\varepsilon)$ indicates the degree of softening. When $K(\varepsilon) \in (0, 1)$, it means that the stress-strain curve is on the lower side of the stress-strain curve of the optimum group, and the smaller $K(\varepsilon)$ is, the further the stress-strain curve is from the stress-strain curve of the optimum group. The smaller the $K(\varepsilon)$ under the same strain, the smaller the stress value is at that time than the stress value of the optimum test group at that strain. This means that the test group is less able to absorb damage energy than the optimum group. When $K(\varepsilon) > 1$, this means that the stress-strain curve is on the upper side of the optimum stress-strain curve and the larger $K(\varepsilon)$ is, the higher the stress-strain curve is above the optimum group stress-strain curve. If $K(\varepsilon) > 1$ under the same strain, the higher the stress value of the test group at this time is that the stress value of the optimum test group at this strain. This means that the test group is more capable of absorbing damaged energy than the optimum group.

As can be seen from Figure 8(a), the trends of $K_{11}$ and $K_{12}$ are opposite. $K_{11}$ is greater than $1$ in the strain range of $0.0005$–$0.0009$, indicating that the test group MC-3 is more capable of absorbing damage energy in the strain range of $0.0005$–$0.0009$ than MC-2. $K_{12}$ shows a decreasing trend before the strain of $0.0008$ and an increasing trend after the strain is greater than $0.0008$, and $K_{12}$ does not exceed $1$. It indicates that MC-4 is less capable of absorbing damage energy than MC-2 up to a strain of $0.0008$. As shown in Figures 8(a)–8(c), $K_{11}$, $K_{12}$, $K_{14}$, and $K_{15}$ all decrease and then increase. It indicates that the ability of MC20-3, MC20-4, MC60-2, and MC60-3 to absorb damage energy decreases...
Table 5: Calculation data.

| Test group | $V$ (MJ/m$^3$) | $A_1$ (MJ/m$^3$) | $A_2$ (MJ/m$^3$) | $T$ (%) |
|------------|----------------|------------------|------------------|---------|
| JZ         | —              | 0.035686         | 0.025249         | 29.247  |
| MC-2       | 0.026056       | 0.036765         | 0.026056         | 29.128  |
| MC-3       | 0.025575       | 0.047076         | 0.039400         | 16.306  |
| MC-4       | 0.020317       | 0.040664         | 0.032969         | 18.923  |
| MC20-2     | 0.036399       | 0.039235         | 0.036399         | 7.2282  |
| MC20-3     | 0.027369       | 0.037605         | 0.027369         | 27.220  |
| MC20-4     | 0.027232       | 0.038460         | 0.027232         | 29.194  |
| MC60-2     | 0.015275       | 0.053477         | 0.042295         | 20.910  |
| MC60-3     | 0.024097       | 0.035263         | 0.024097         | 31.665  |
| MC60-4     | 0.024779       | 0.056131         | 0.050356         | 10.288  |
| MC80-2     | 0.013151       | 0.019239         | 0.013151         | 31.644  |
| MC80-3     | 0.010541       | 0.031131         | 0.016295         | 47.657  |
| MC80-4     | 0.011690       | 0.027543         | 0.021342         | 22.514  |

Table 6: Softening curves.

| Test group | Softening curves of $K(\epsilon)$ | The direction of softening |
|------------|----------------------------------|---------------------------|
| MC-3       | $K_{a1}$                         | From MC-2 to MC-3         |
| MC-4       | $K_{a2}$                         | From MC-2 to MC-4         |
| MC20-3     | $K_{b1}$                         | From MC20-2 to MC20-3     |
| MC20-4     | $K_{b2}$                         | From MC20-2 to MC20-4     |
| MC60-2     | $K_{c1}$                         | From MC60-4 to MC60-2     |
| MC60-3     | $K_{c2}$                         | From MC60-4 to MC60-3     |
| MC80-3     | $K_{d1}$                         | From MC80-2 to MC80-3     |
| MC80-4     | $K_{d2}$                         | From MC80-2 to MC80-4     |

Figure 8: Continued.
Figure 8: Softening curves. (a) Softening curves of $K_{a1}(\varepsilon)$ and $K_{a2}(\varepsilon)$. (b) Softening curves of $K_{b1}(\varepsilon)$ and $K_{b2}(\varepsilon)$. (c) Softening curves of $K_{c1}(\varepsilon)$ and $K_{c2}(\varepsilon)$. (d) Softening curves of $K_{d1}(\varepsilon)$ and $K_{d2}(\varepsilon)$.

Figure 9: Continued.
and then increases compared with the optimal group MC20-2 and MC60-4. As can be seen from Figure 8(d), $K_{d1}$ and $K_{d2}$ are the smallest in the strain value range of 0.0003–0.0004, which indicates that the MC80-3 and MC80-4 groups have the weakest ability to absorb damage energy in the strain value range of 0.0003–0.0004.

3.4. Morphology and Distribution of Rubber Powder and Fiber in Concrete

3.4.1. Imaging Analysis by RapidAir457 System. To investigate the distribution of pasture fibers in rubber powder concrete, we used a RapidAir 457 system to scan and
photograph the pasture fibers in the sample. The RapidAir 457 system has an analysis area of 60 mm × 60 mm. The striped fluorescence areas are pasture fiber stalk cross-sections, rubber powder, and air bubbles. The larger areas of speckled fluorescence are the pasture fiber stalk sections.

As can be seen in Figures 9(a), 9(d), and 9(g), when the pasture fiber admixture is 2 kg/m³, the image contains less pasture fiber but is more evenly distributed. The small fluorescent spots (rubber powder and air bubbles) are also more evenly distributed. This indicates that with less pasture fiber, the pasture fiber, and rubber powder can be evenly mixed and the air bubbles introduced during the mixing process are also more evenly distributed. As can be seen from Figures 9(b), 9(e), and 9(h), when the pasture fiber admixture is 3 kg/m³, the pasture fiber content in the image increases significantly and the position of the pasture fibers is distributed parallel to the image and perpendicular to the image, indicating the formation of a net-like organization within the concrete. As can be seen from Figures 9(c), 9(f), and 9(i), the distribution of pasture fibers in MC60-4 and MC80-4 is not uniform when the pasture fiber admixture is 4 kg/m³. For example, there is no pasture fiber distribution in the middle area of Figure 9(f) and no pasture fiber distribution in the lower right area of Figure 9(i). It is because the 60 mesh and 80 mesh rubber powders have smaller particle sizes compared with the 20 mesh small rubber powders and are not easily mixed in concrete when the pasture fibers are mixed in larger amounts, resulting in both being even less easily mixed.

3.4.2. Imaging Analysis by Scanning Electron Microscopy. As can be seen in Figures 10(a) and 10(b), the pasture fibers show pull-off damage, indicating that the pasture fibers absorb the energy of the damage by breaking themselves. Figure 10(c) shows intact pasture fibers penetrating the area of concrete where they are located. It can be inferred that the pasture fibers in the concrete formed a web-like structure through the concrete. Figure 10(d) shows the rubber powder in the concrete and Figure 10(e) indicates the location of the energy spectrum test pick-up point for the rubber powder in Figure 10(d). Figure 10(f) shows the energy spectrum test curve. Figure 2(b) shows the energy spectrum measured when the rubber powder was not incorporated into the concrete. Comparing Figures 10(b) and 10(f), it can be seen that there is a significant increase in the elemental content of Al, Fe, and Si on the surface of the rubber powder in the concrete, which indicates that the rubber powder in the concrete is covered with a cementitious material. The rubber powder is connected to the concrete through the cementitious material wrapped on the surface. Figure 10(g) shows a small crack in the bond between the modified pasture fiber and the cementitious material. This shows that there will still be a weak interface between the modified grass fibers and the concrete. Figure 10(h) shows that a weak interface also exists between the rubber powder and the concrete material. Figure 10(i) shows the presence of two rubber powder particles, which indicates that the rubber powder is not easily mixed and can appear to agglomerate.

4. Conclusion

(1) The incorporation of modified pasture fiber and rubber powder can absorb the damage energy through the deformation of the rubber powder itself and the tensile fracture of the pasture fiber, thereby enhancing the deformation performance of the concrete. The slope of the rising section of the stress-strain curve of the test group with modified pasture fiber and rubber powder is lower than that of the reference group because the incorporation of these two materials, which lack stiffness, impacts the overall stiffness of the concrete material. The concrete composed of 80 mesh rubber powder and modified pasture fibers (2 kg/m³, 3 kg/m³) has abrupt internal structural damage when the peak load is reached.

(2) The peak loads of 20 mesh and 60 mesh rubber powder concrete with 3 kg/m³ of pasture fiber are higher than other mixed amount pasture fiber test groups. Since the internal network structure is more conducive to limiting the development of internal damage before peak load and delaying plastic failure when the mixed amount of pasture fiber is 3 kg/m³ in 20 mesh and 60 mesh rubber powder concrete.

(3) Analysis of the electron microscope scan photographs revealed that the pasture fibers modified with 3% sodium hydroxide solution still had a weak interface with the concrete material but the weak interface was not obvious. This modification method does not fundamentally change the nature of the pasture fiber as a waste construction material, but only enhances the degree of bonding between the pasture fiber and the concrete material.

(4) The compressive toughness loss rate of MC60 groups and MC80 groups increased at first and then decreased with the increase of pasture fiber content, indicating that the compressive toughness of these two groups decreased and then increased with the increase of pasture fiber content from 2 kg/m³ to 4 kg/m³. In 20 mesh rubber powder concrete, an increase in the amount of modified pasture fiber admixture reduces the compressive toughness of the concrete.

(5) The analysis of the softening curves shows that MC-3 has a stronger ability to absorb damage energy than MC-2 in the strain range of 0.0005–0.0009. MC-4 has a weaker ability to absorb damage energy compared to MC-2 until the strain is 0.0008. After strains above 0.0008, MC-4 becomes progressively more capable of absorbing damage energy but weaker than MC-2. MC80-3 and MC80-4 groups are the least capable of absorbing damage energy in the strain range of 0.0003–0.0004.
The imaging analysis with the RapidAir457 system revealed that at a pasture fiber admixture of 3 kg/m³, the position of the pasture fibers was distributed parallel to the image and perpendicular to the image, indicating the formation of a web-like organization within the concrete. At a pasture fiber admixture of 4 kg/m³, the distribution of pasture fibers in MC60-4 and MC80-4 was not uniform.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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