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Study on the Mechanical Properties and Durability of Tunnel Lining Concrete in Coastal Areas

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Abstract: To address the problems of the lining cracking and spalling in tunnel structures in coastal areas under the influence of special geological conditions, environmental loading, and the coupling effect of chemical erosion, hybrid fibers were introduced to fly ash concrete in this study. The working performance, compressive strength, split tensile strength, and flexural strength of the hybrid fiber fly ash concrete were tested. A chloride diffusion coefficient under steady-state conditions and a durability test for resistance to sulfate corrosion were carried out. Thus, in-depth analyses of the comprehensive performance of the hybrid fiber fly ash concrete used for the tunnel lining were carried out and the damage mechanism was explored. The results showed that the hybrid fiber fly ash concrete exhibited higher strength compared to the concrete in the control group. However, when the fibers exceeded a certain dosage, the reduction in the working properties of the concrete structure led to the creation of larger pores in the matrix structure, which in turn affected the mechanical properties of the concrete. The most significant reduction in the chloride diffusion coefficient was observed when both steel fibers and coconut fibers were added at a 1.0% volumetric parameter, compared to the control group. The apparent state and compressive strength after sulfate corrosion were also minimally affected. This study ensured that the mechanical properties of the concrete were improved and the corrosion resistance of the matrix also substantially improved, providing a scientific basis for improving the performance of tunnel lining concrete, and confirming that steel–coconut hybrid fiber fly ash concrete has a great potential to improve the structural load-bearing capacity and durability, which may provide theoretical support for its continued use in tunneling projects and construction processes.

Keywords: tunnel lining concrete; persistence; steel fiber; coconut fiber; mechanism analysis ergonomics

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1. Introduction

Concrete is the key material for tunnel lining; for tunnel structures in coastal areas, it must withstand not only the pressure from environmental loads, but also resist the occurrence of erosion phenomena such as galvanic corrosion. When the bearing capacity of the concrete structure is insufficient or the structure is eroded by chloride ions and sulfate ions for a long period, the tunnel lining concrete is very susceptible to cracking.

The cracks on the surface of the lining are distributed in a discontinuous and random manner. These cracks gradually form and expand under the long-term action of multiple loads such as hydrostatic pressure, ground stress, and dynamic load. This eventually leads to deterioration and dislodgement of the concrete structure, causing serious safety hazards. The use of fibers can significantly improve the mechanical properties and durability of tunnel lining concrete in coastal areas, guaranteeing the long-term stable operation of tunnel structures.

Fly ash concrete is now widely used in engineering. The use of fly ash instead of cement in tunnel lining structures can re-purpose waste material, while economising on

required cement quantity in the concrete mix. However, this may have adverse effects on the concrete, such as a loss of concrete strength, which seriously affects the safety and durability of tunnel structures. Adding fibers to fly ash concrete has thus become an effective way to solve this phenomenon.

Steel fibers can improve the toughness of concrete to a certain extent. However, they cannot absorb sufficient energy to prevent the occurrence of fractures when the concrete is subjected to large deformations or severe impacts. Tiberti et al. [1] investigated the use of steel fiber concrete with a partial wire mesh lining to determine the feasibility of using a steel fiber concrete lining to reinforce the critical connection zone between a tunnel's up arch and the steps. Kaufmann W et al. [2] found that adding fibers to concrete is very beneficial for the shear transfer across cracks. This is because the fiber stresses perpendicular to the crack plane are balanced by the compressive stresses on the crack face. These compressive stresses greatly enhance aggregate interlocking. Tests by Kooiman et al. [3] showed that steel fiber concrete has a high tensile stress resistance and can effectively reduce ductile damage and mitigate cracking when properly incorporated into concrete. Wu et al. [4] analyzed the effect of different types and dosages of steel fibers on the performance of concrete and finally found that an increase in the amount of fibers increased the compressive and flexural strength of UHPC and decreased shrinkage. The optimum fiber content for strength and shrinkage was 2%, with a slight increase in strength and a slight decrease in shrinkage above 2%. At a given fiber content, the use of hooked fibers was most effective in increasing the fiber-to-matrix bond strength and flexural strength and reducing shrinkage. Buratti et al. [5] found that steel fibers can optimally reduce the thickness of the tunnel lining and the bridging effect of the fibers can significantly reduce the crack width in the tunnel lining. Zhang et al. [6] prepared two sets of high-flow steel fiber concrete (HF-SFRC) doped with silica fume or fly ash and tested them. The synergistic effect between the fly ash or silica fume, the steel fibers, and the cement in the mixtures enhanced the flowability and improved the mechanical properties of HF-SFRC. Wu et al. [7] investigated the effect of the type and dosage of steel fibers on the abrasion resistance of fibrous concrete. The results showed that the short straight fibers and medium hooked-end fibers had a better distribution of space and a bridging effect, with a better resistance to debris flow abrasion. Nehdi et al. [8] conducted a preliminary study on ultra-high-performance steel fiber concrete tunnel lining pipe sheets with different steel fiber lengths and admixtures. It was found that the short fibers were more capable of improving the strain-hardening phase of the lining concrete and were fully capable of replacing the steel reinforcement in corrosive environments. Chiaia et al. [9] investigated the application of steel fibers in a cast-in-place steel fiber concrete tunnel lining in both normal service conditions and extreme conditions, and the corresponding structural advantages, finding that the fibers were able to reduce the crack width. Shao G.d. [10] took samples from the inner and outer surfaces of a tunnel lining and studied the anti-chlorine ion penetration performance. The results showed that the chloride ion diffusion coefficient of steel fiber concrete was reduced by 34% to 41% in comparison to ordinary concrete, and the steel fibers could effectively prevent the diffusion of chloride ions in the concrete and were better located in the inner side of the tunnel. You [11] et al. added synthetic steel fibers into concrete and concluded that coarse synthetic steel fibers improved the densification of the concrete structures and inhibited the entry of sulfate ions into the interior of the concrete, thus reducing the degradation of concrete by sulfate. By studying the load-bearing characteristics of plain concrete, reinforced concrete, and steel fiber concrete lining, it was found that steel fibers can improve the load-bearing capacity of the lining structure, but more cracks are seen in steel fiber concrete lining and the development path is more tortuous [12]. Liu et al. [13] found that after adding steel fibers to concrete, the mechanical properties and the ability to resist the fracture of concrete were improved, but the working ability decreased to a certain extent. Cui et al. [14] investigated the damage mechanism of fiber concrete lining in tunnel applications by carrying out flexural simulation tests and found that the flexural effect of mixed fiber concrete lining was better than that of steel fiber concrete lining. Therefore, the

addition of plant fibers with superior toughness, based on single mixed steel fibers, can substantially enhance the flexural and tensile properties of concrete.

The introduction of coconut fibers significantly improves the toughness of fly ash concrete and enhances the ductility of the structure's performance during flexural actions. Additionally, the corrosion resistance of coconut fibers makes them excellent at resisting harsh environmental factors, such as chloride-induced attack and sulfate corrosion. This makes coconut fibers an ideal choice for construction materials in coastal and other challenging environmental conditions. Chain-arranged cellulose molecules form the basis of coconut fibers and largely determine the tensile properties of plant fibers [15]. Ali et al. [16] discussed the suitability of coconut fiber-reinforced concrete in various projects and concluded that coconut fibers can improve the tensile strength, flexural strength, and fracture toughness of concrete. Hwang et al. [17] found that the addition of coconut fibers to concrete had a positive effect on the initial crack deflection, toughness index, plastic cracking, and the impact resistance of the composites. Reis [18] conducted a three-point bending test to investigate the flexural strength and fracture toughness of epoxy polymer concrete reinforced with coconut, bagasse, and banana fibers. It was found that the coconut fiber-reinforced polymer concrete had the highest fracture toughness, and the coconut fibers increased the flexural strength of concrete by 25%. Wu Hui [19] et al. added coconut fibers (CFs) to magnesium phosphate cement and tested its compressive properties. The results showed that when the CF dosage was higher than 1%, the brittleness of the magnesium phosphate cement was significantly reduced, and the specimen's damage morphology changed from brittleness to a certain degree of ductility when the CF dosage was 2%. Ahmad et al. [20] investigated the effect of coconut fibers with different lengths and volumetric additions on the properties of high-performance concrete and found that the best overall performance was obtained with a coconut fiber length of 50 mm and a volume addition of 1.5%. While they enhance the toughness of a concrete matrix, coconut fibers are also beneficial in terms of concrete durability. Ramli et al. [21] investigated the strength and durability of coconut fiber concrete in aggressive environments, such as with seawater and air exposure, for different amounts of time. The microstructure and durability tests, such as the depth of carbonation, intrinsic permeability, and chloride ion penetration tests, were investigated using a scanning electron microscope and X-ray diffractometer. It was found that due to the incorporation of coconut fibers, durability properties such as the chloride ion permeability were improved in addition to the improvement in compression and flexural properties. B. Ali et al. [22] summarized the literature on coconut fibers as a reinforcing material for concrete and found that although coconut fibers improve the toughness of concrete, the improvement in compressive strength and the modulus of elasticity of concrete is limited.

Tunnels in coastal areas are not only subjected to environmental loads and other external forces, but also suffer from corrosion caused by many chloride salts, sulfates, and other aggressive ions, resulting in phenomena such as cracking and spalling. Steel fibers have good mechanical properties and coconut fibers can improve the toughness and durability of concrete structures, so the complementary role of the two fibers is very suitable for tunnel lining in a coastal environment. In this study, the chloride diffusion coefficient test, as well as the sulfate corrosion test, was carried out to test the working and mechanical properties of concrete. In addition, in-depth structural analyses of the reinforcement mechanism of the fibers in fly ash concrete were carried out in this study, with the aim of revealing the interaction between the fibers and the concrete matrix and its effect on the macroscopic properties of the material.

2. Materials and Methods

2.1. Test Preparation

2.1.1. Raw Materials

The cementitious materials used in this study were locally produced P·O42.5R ordinary silicate cement and 1250 mesh secondary fly ash. Medium sand with a fineness modulus of 2.7 was used as the fine aggregate in this study and crushed stone with a diameter of

5–20 mm was selected for the application of coarse aggregate. The bulk densities of the coarse and fine aggregates were 1.73 g/cm^3 and 1.43 g/cm^3, respectively. The aggregate particle gradation is shown in Figure 1. Polycarboxylate superplasticizer was used as an admixture, the steel fibers selected were 40 mm end-hook type steel fibers, and coconut fibers with a length of 40~50 mm were selected. The physical properties of the fibers are shown in Table 1, and the fiber shapes are shown in Figure 2.

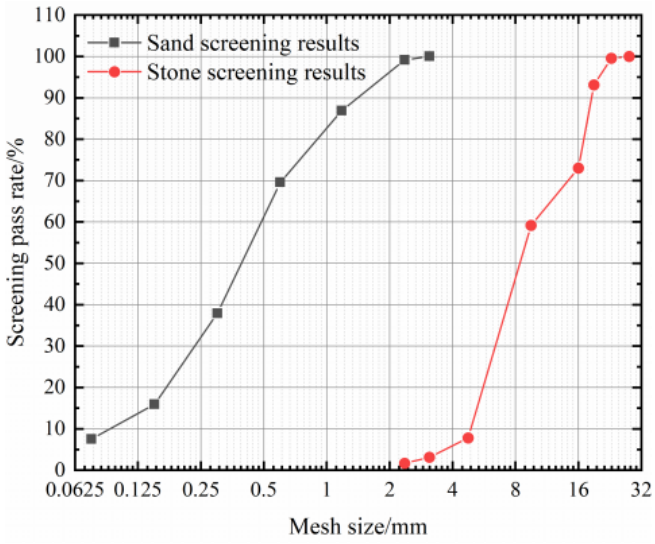


Figure 1. Aggregate particle grading table.

Table 1. Physical properties of the fibers.

Fiber Class	Length (mm)	Diameter (mm)	Density(g/cm^3)
Steel fiber	40	4	7.90
Coconut fiber	40-50	0.4	1.12



(**a**) (**b**)

Figure 2. Fiber pictures. (**a**) Steel fiber. (**b**) Coconut fiber.

2.1.2. Mixing Ratio

To investigate the effect of different volumetric additions of steel fibers and coconut fibers on the properties of fly ash concrete, in this experiment, the steel fibers were divided into five volumes of content: 0%, 0.5%, 1.0%, 1.5%, and 2%. Coconut fibers were divided into six volumes of content: 0%, 0.5%, 0.75%, 1.0%, 1.25%, and 1.5%. The fibers were added to the fly ash concrete in different combinations, and the mechanical properties and durability of the test blocks were tested. The concrete mixing ratio is shown in Table 2.

Table 2. Mixing ratio.

Water to Cement Ratio	Water	Binding Material	Fine Aggregate	Coarse Aggregate	Admixture
			kg/m^3		
0.5	195	390	672.2	1142.8	1.95

2.1.3. Preparation of Specimens

In the preparation of specimens for this test, coconut fibers were first soaked for 12 h to remove any adhering impurities, dried in the sun, then cut into small segments of 4–5 cm in uniform length. The coarse aggregate was sieved to remove fine particles and dust impurities to ensure cleanliness and consistency in the aggregate size. The sand was sieved to remove individual particles with a large diameter. Coarse aggregate, fine aggregate, cement, and fly ash were poured into the mixer in a sequential order. After 2 min of mixing, steel fibers and treated coconut fibers were gradually and uniformly spread into the mixer, and mixing was continued until the fibers were well mixed with the concrete matrix. Water pre-mixed with polycarboxylate superplasticizer was added to the mixer and mixing was continued until a homogeneous concrete mix was formed. After being placed in the mold, the concrete was vibrated using a vibrating table until no obvious air bubbles were visible outside the concrete. The surface was smoothed, covered with plastic film, then watered to keep it moisturized for 24 h. After that, the concrete was removed and placed in a maintenance room at 18 °C to 22 °C with a humidity of 95% or more for 28 days to ensure that the concrete reached the design strength.

2.2. Test Methods

2.2.1. Compression Test, Splitting Tensile Test, and Flexural Test

This test was based on GB/T 39698-2020 [23], JGJ 52-2006 [24], GB/T 50081-2019 [25], and GB/T 50082-2009 [26]. For the mechanical property tests, each mix was tested in a group of three test blocks, where the compressive and splitting tensile test blocks were 100 mm × 100 mm × 100 mm in size, and the flexural test blocks were 100 mm × 100 mm × 400 mm in size. The pressure testing machine specialty was utilized to test the mechanical properties of the blended fiber concrete blocks after curing them for 28 d in the standard conditions (Figure 3). The loading rates of the compression test, splitting tensile test, and flexural test were 0.5 MPa/s, 0.05 MPa/s, and 0.05 MPa/s, respectively.

(1) The principle of the compressive strength test is as follows:

$$f_{cc} = \frac{F}{A}, \tag{1}$$

where f_{cc} represents the compressive strength (MPa) of the concrete cube specimens, with calculation results that should be accurate to 0.1 MPa, F represents the failure load of the specimen (N) and A represents the compressive area of the specimen (mm^2).

(2) The principle of splitting tensile strength test is as follows:

$$f_{ts} = \frac{2F'}{\pi A'} = 0.637\frac{F'}{A'}, \tag{2}$$

where f_{ts} represents the splitting tensile strength of concrete (MPa), F' indicates the failure load of the specimen (N), and A' represents the splitting surface area (mm^2) of the specimen.

(3) The principle of flexural strength test is as follows:

$$f_f = \frac{F''l}{bh^3}, \tag{3}$$

where, f_f represents the flexural strength of concrete (MPa), F'' represents the load when the specimen is destroyed (N), l is the bearing span (mm), b is the width of the cross-section of the specimen (mm), and h is the height of the cross-section of the specimen (mm).



Figure 3. Pressure testing machine specialties and models.

2.2.2. Chloride Diffusion Coefficient Test

(1) According to the standard, φ 100 × 50 mm cylinder test blocks were made. The three test blocks were a group. After 28 days of curing, the vacuum-saturated salt treatment was carried out. The machine is shown in Figure 4a. The NEL-PDR chloride diffusion coefficient tester was used to test the chloride ion permeability of the test blocks, as shown in Figure 4b. The NEL-PDR chloride ion diffusion coefficient rapid tester is a concrete permeability tester developed using the chloride ion diffusion coefficient test principle proposed by Professor Lu. The device can quickly detect the chloride ion diffusion coefficient in concrete, to evaluate the permeability of concrete.

(2) The test used the method proposed by Professor Lu [27] of Tsinghua University. The test principle was based on the Nernst–Einstein equation. The concrete is regarded as a solid electrolyte, and the diffusion coefficient of the charged particle i in the concrete is related to its partial conductance. On this basis, if the concentration Ci of the ion i and the partial conductance are known, it is easy to obtain the diffusion coefficient of the ion i. After vacuum-saturated salt treatment, there is only one ion in the specimen—Cl^-. At this time, it can be assumed that the ion migration number of the specimen is 1 and the chloride ion concentration in the concrete pore solution is Ci. The formula is (4).

$$D_{\mathrm{i}} = \frac{RT\sigma_{\mathrm{i}}}{Z_{\mathrm{i}}^2 f^2 C_{\mathrm{i}}^2}, \tag{4}$$

where D_i is the diffusion coefficient of charged particle i, s/m; σ_{i} is the partial conductivity of charged particles, s/m; R is the gas constant, equal to 8.314 J/mol·K; T is the absolute temperature—if it meets the laboratory standard temperature, the value is 298 K; Z_i is the charge number of charged particles, i; f is the Faraday constant, taking 96,500 Coul/mol, and C_i is the number concentration of charged particles, cm^3/mol.



(**a**) (**b**)

Figure 4. (**a**) Salt saturation instrument. (**b**) NEL-PDR chloride diffusion coefficient tester.

2.2.3. Sulfate Corrosion Resistance Test

According to the specification, cube test blocks 100 mm × 100 mm × 100 mm in size were made. Three test blocks were used as a group. The test was started after 26 days of curing. The test pieces were soaked in 5% Na_2SO_4 solution for (15 ± 0.5) h, and the solution was quickly emptied. After drying for 30 min, the solution was heated to 80 °C within 30 min, dried at (80 ± 5) °C for 6 h, cooled to 25~30 °C within the last 2 h, and put into 5% Na_2SO_4 solution again to enter a new round of circulation. The total duration of each dry–wet cycle was (24 ± 2) h. A total of 60 cycles were conducted. After the cycles, the apparent state and strength loss rate of the concrete test blocks were observed and tested. The strength loss rate (5) formula is as follows:

$$f_{cc}{}' = \frac{f_{cc1} - f_{cc0}}{f_{cc0}}, \quad (5)$$

In the formula, $f_{cc}{}'$ is the percentage of the compressive strength loss rate (%) of the cube concrete test block, f_{cc0} is the initial compressive strength of the specimen (MPa), and f_{cc1} is the compressive strength (MPa) of the specimen after the dry–wet cycle is completed.

3. Analysis and Discussion of Results

3.1. Slump Value

The specimen slump decreased with increasing fiber content. Figure 5 shows the effect of the fiber admixture on the slump—all fly ash concretes admixed with fibers had less slump than the control. This was consistent with the findings of [28], where the interlocking of fibers affected their slump values compared to the control. While the cementitious material had some water absorption, the addition of fibers to the concrete mixture hindered the flow of the concrete [29,30]. Higher fibers in fresh concrete mixtures resulted in a tendency for the fibers to ball up, which reduced the slump considerably. However, too small a slump value would have a reduced effect on the compatibility of the concrete mix, making it inconvenient for construction.

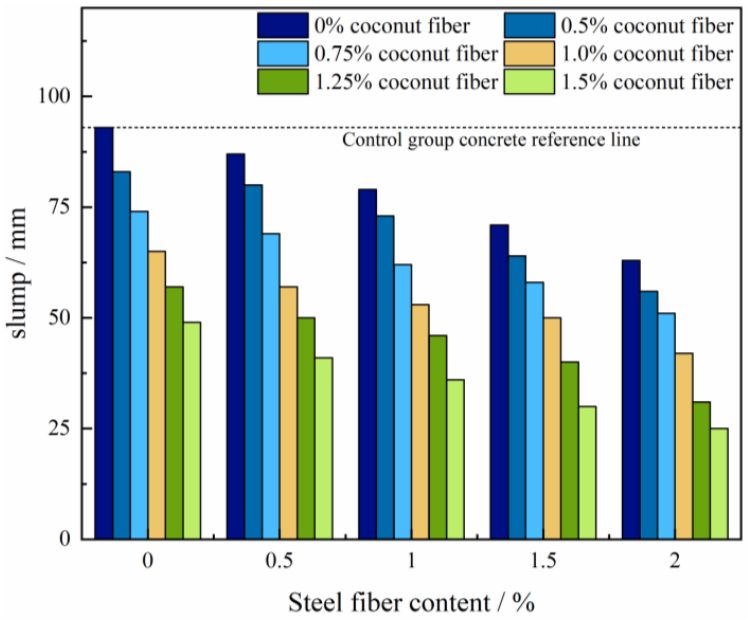


Figure 5. Graph of slump values.

3.2. Mechanical Properties of Concrete

3.2.1. Compressive Strength

The compressive strength of the fly ash concrete specimen with a different volumetric admixture of steel fibers and coconut fibers is shown in Figure 6. As shown in the figure, the compressive strength of the specimen with different coconut fiber admixtures showed a trend of increasing then decreasing with the increase in steel fibers. Without adding any fibers, the compressive strength of the matrix was 29.41 MPa. At this time, when the test blocks were damaged, they showed the characteristics of brittle damage, and the outer wall of the test blocks were detached, as shown in Figure 7. After mixing with steel fibers and coconut fibers alone, the compressive strength increased up to 32.56 MPa and 39.3 MPa. The strength of the steel fibers was higher than that of coconut fibers, resulting in an overall strength greater than that of coconut fibers mixed alone.

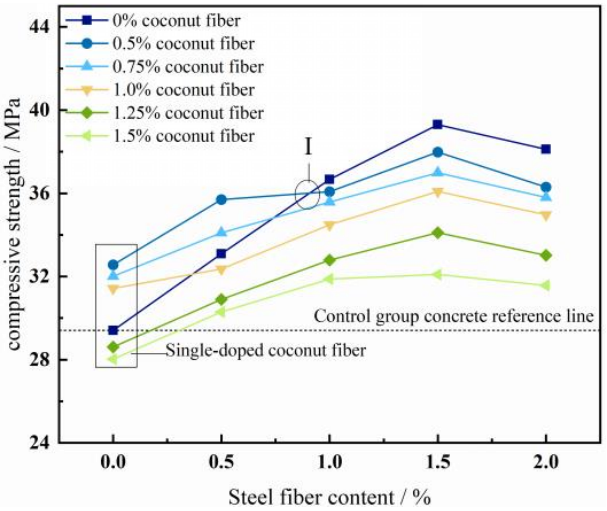


Figure 6. Compressive strength curve of specimen.



Figure 7. The failure pattern of the control group specimen.

There was also a substantial increase in compressive strength when blended; the compressive strength of the fly ash concrete specimens with the addition of 1.5% steel fibers and 0.5% coconut fibers was enhanced by 29.1% compared to the control group. In a study by Song [31], the compressive strength of the concrete matrix was enhanced by 15% with the addition of fibers. With the increase in the steel fiber admixture, the fibers were distributed longitudinally and horizontally in the concrete, changing the structure of the concrete matrix while generating more voids. After adding a small amount of coconut fibers, the overall structure of the concrete interior was improved and through the combined effect of steel fibers and coconut fibers, the coconut fibers substantially prevented cracking. The steel fibers prevented the pressure from spreading around the concrete after compression, and the two demonstrated higher performance synergistically. However, when the steel fiber admixture exceeded 1.5% and the coconut fiber admixture exceeded 1.0%, regardless of the admixture method, the compressive strength of the fly ash concrete was negatively affected in this study, which was in agreement with the experimental results of many researchers who found that excessive fibers lead to loss of the compressive strength of concrete [32,33].

The reason for the occurrence of I may be that when the coconut fiber dosage was 0.5%, with the increase in the steel fiber dosage, the fly ash concrete matrix structure produced larger pores which ultimately led to a reduction in the compressive strength, which was lower than the compressive strength when steel fibers were dosed alone. The phenomenon of the test block is shown in Figure 8.

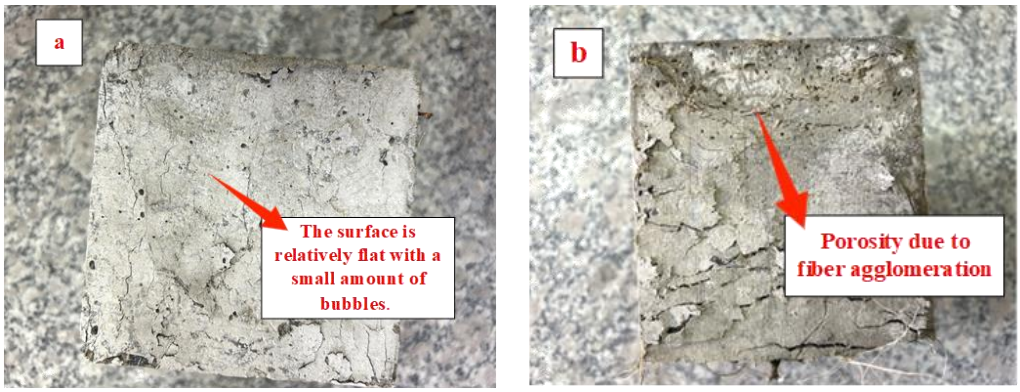


Figure 8. (**a**) Steel fiber (1.0%) specimen picture; (**b**) steel fiber (1.0%), coconut fiber (0.5%) specimen pictures.

3.2.2. Splitting Tensile Strength

The splitting tensile strength of the fly ash concrete specimen is shown in Figure 9. Without any fiber admixture, the concrete specimen undergoes sudden brittle damage and the cracks expand and penetrate through the entire cross-section of the specimen, splitting

it in two, as shown in Figure 10a. The maximum increase in split tensile strength was 15.7% when 1.5% steel fibers alone was added to the matrix, and 16.1% when 1.0% coconut fibers alone was added to the matrix. The damage mechanism of the concrete with fibers was very different from the control group. It is evident from Figure 10b that due to the bridging effect of the fibers, the fibers prevented the matrix from cracking completely, allowing the brittle damage of the concrete to be transformed into ductile damage. Among the mixed fibers, 1.0% steel fibers and 1.0% coconut fibers effectively enabled the enhancement of the splitting tensile strength of the concrete specimens by 22.6%. A study by Yufei Xie [34] found that the addition of steel fibers increased the matrix splitting tensile strength by 15.56% compared to normal concrete. It indicated that the synergistic effect of the mixed fibers plays a greater role. This result agreed with the findings of Sivakumar et al. [35] with regard to increasing the tensile strength of concrete, concluding that the increase in strength came from the combination of metallic and non-metallic fibers.

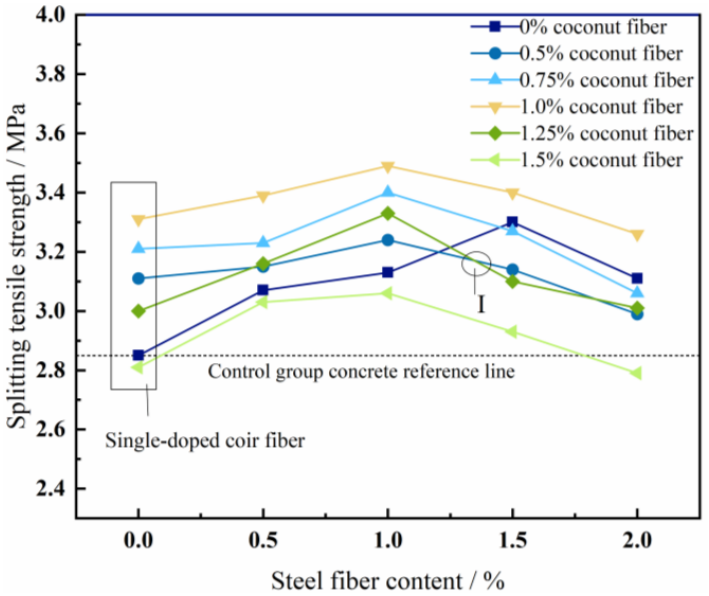
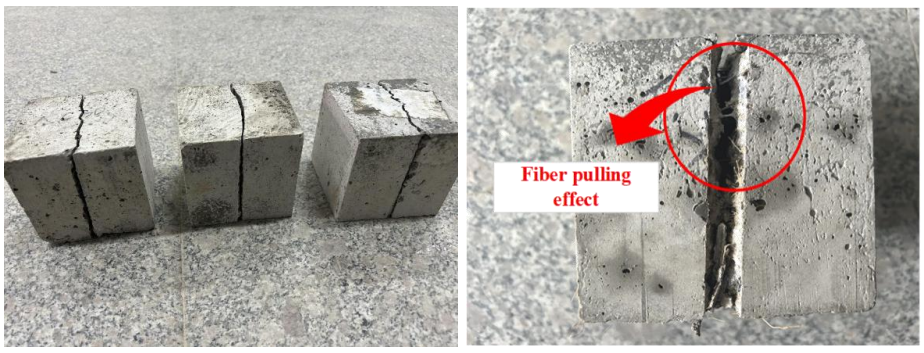


Figure 9. Split tensile strength curve of specimen.



(**a**) (**b**)

Figure 10. Specimen splitting tensile damage morphology. (**a**) Control fly ash concrete, (**b**) hybrid fiber fly ash concrete.

A small number of fibers can fill the holes in the concrete and make the inside of the specimen denser, allowing the load to be dispersed uniformly. However, when too many fibers were mixed, the phenomenon of agglomeration occurred and the fibers were unevenly distributed in the concrete. This led to a deterioration in compatibility and also resulted in larger pores forming inside the concrete, which in turn led to a decrease in the splitting tensile strength.

The reason for I is that the fiber distribution is uneven due to the machine factors in the laboratory. Finally, the coconut fiber agglomeration leads to errors when the mold is manually installed.

3.2.3. Flexural Strength

The flexural strength of the concrete specimens is shown in Figure 11. Same as the compressive strength and splitting tensile strength patterns, the flexural strength of the specimen blocks showed a tendency to increase and then decrease with the increase in fibers. As shown in Figure 12a, the control fly ash concrete specimens produced brittle damage and fractured as expected. The bridging effect of the fibers was more clearly demonstrated compared to the splitting tensile strength. As shown in Figure 12b, depicting the fracture picture when steel fibers alone were added, the steel fibers were distributed longitudinally and transversely in the matrix, and the crack openings in the specimens were significantly wider than those in the fiber-mixed specimens (Figure 12c). The highest flexural strength was obtained when both steel fibers and coconut fibers were mixed at 1.0%, showing an improvement of 26.58% compared to the control. The specimens did not fail rapidly after the small cracks were produced, as shown in Figure 13, but the cracks gradually spread towards the top of the specimen as the deformation increased. The strain growth in the cross-sectional region accelerated with further increase in stress, and finally the specimen was destroyed when the width of the cracks reached 6.96 mm. This was in line with the trend in the results of Das et al. [36], who tested the mechanical properties of blended fiber concrete and found that the most significant effect on flexural enhancement was observed with a 1.0% coconut fiber admixture.

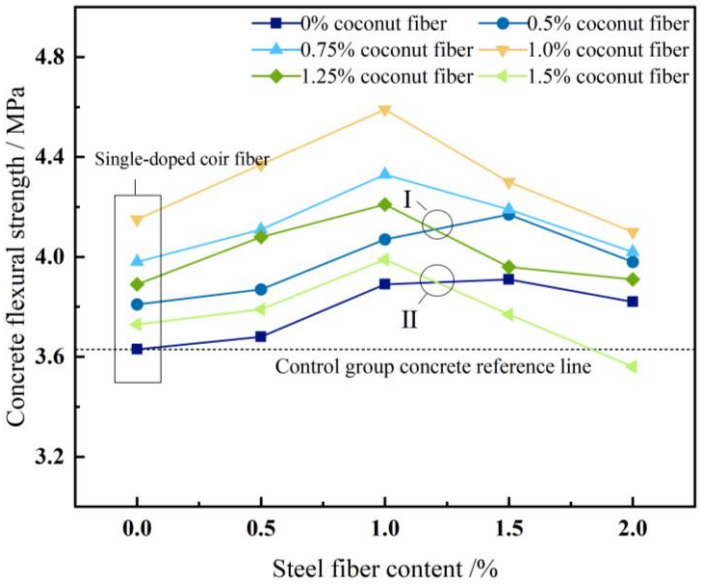


Figure 11. Flexural strength curve of specimen.

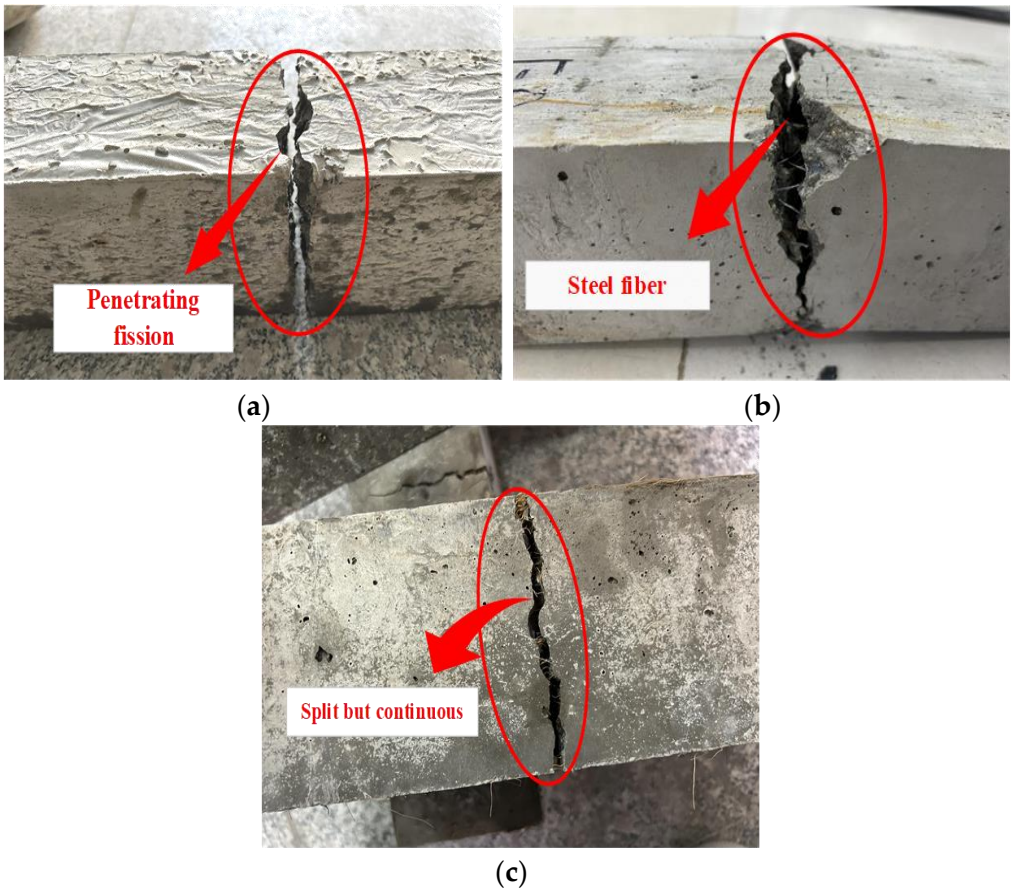


Figure 12. Fracture damage morphology of specimens. (**a**) Control specimen, (**b**) single doped steel fibers specimen group, (**c**) mixed fiber specimen group.

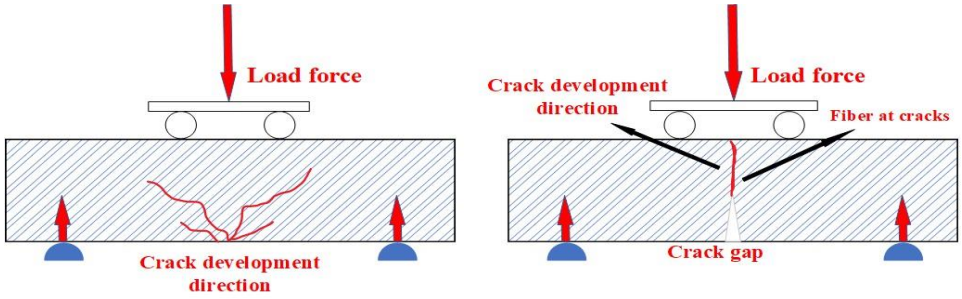


Figure 13. Force distribution of specimen.

The reasons for I and II may be that too much coconut fiber was mixed in. Because the weight of the coconut fiber is light, when its volume fraction increases, the number of fibers surges. This leads to a deterioration in the ease with which the concrete matrix can be churned, making it difficult to achieve complete mixing. As a result, a delamination phenomenon occurs, as shown in Figure 14, which causes a reduction in strength.



Figure 14. Phenomenon of specimen delamination.

3.3. Concrete Durability Properties

3.3.1. Chloride Diffusion Coefficient

The steady state chloride diffusion coefficient graph of the fly ash concrete specimens is shown in Figure 15. Figure 16 shows some of the specimens. Figure 17 shows the schematic diagram of the test. As can be seen in Figure 15, it was found that the addition of 1.5% coconut fibers and 2.0% steel fibers increased the diffusion coefficient by 12.6% compared to the control. This indicated an increase in the permeability of the concrete to chloride ions. This phenomenon was indicative of the possible adverse effect of excess fiber incorporation on the permeability of concrete. Excessive fiber incorporation reduces the dispersion of fibers, which makes it difficult to disperse the fibers during the mixing process. Subsequently, they tend to form a solid mass and introduce many additional air bubbles, which leads to many air holes remaining in the concrete after hardening. This not only provides more channels for ions to enter the interior of concrete, but also improves the penetration rate of chloride ions in the interior of concrete. A study by Bai Min et al. [37] reached a similar conclusion, pointing out that when the fiber admixture exceeds a certain threshold, the internal pore structure of concrete deteriorates, which is not conducive to improving the resistance of concrete to chloride ion erosion.

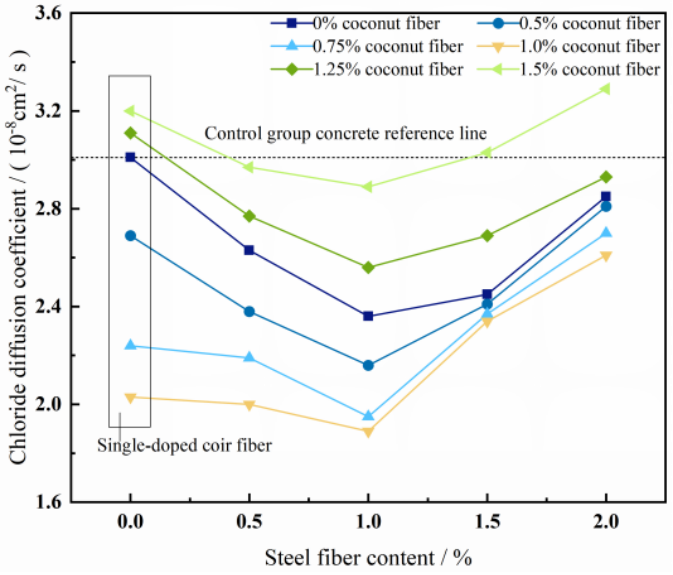


Figure 15. Chloride diffusion coefficient graph.



Figure 16. Testing specimen.

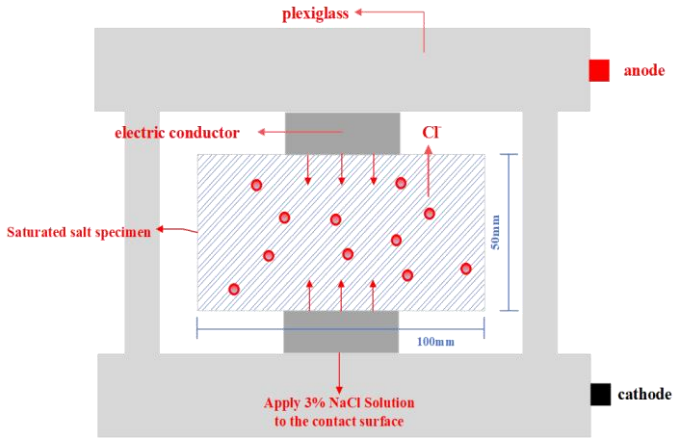


Figure 17. Schematic diagram of chloride ion diffusion mechanism.

From Figure 15, it can be seen that most of the chloride diffusion coefficients of the concrete tended to decrease after the addition of fibers. The inhibition of chloride ion diffusion was most pronounced when steel fibers and coconut fibers were incorporated at a volume admixture of 1.0%, respectively. The addition of an appropriate amount of fiber concrete effectively inhibited the formation and development of shrinkage microcracks during the hardening process. This was because the presence of microcracks largely increases the penetration rate of chloride ions within the concrete. The crack-blocking effect of fibers plays a role, and the randomly distributed hybrid fiber fly ash concrete reduces the possibility of penetrating cracks being generated. This effect is pictorially described in engineering practice as the synergistic effect of "1 + 1 > 2", which not only strengthens the cohesion of the concrete, but also improves the pore structure of the concrete at the microscopic level and reduces the connectivity of the pores, thus significantly improving the anti-chlorine ion permeability of the tunnel lining.

3.3.2. Resistance to Sulphate Corrosion

Sulfate erosion damage is a very complex physicochemical process. In essence it is due to the external erosion medium entering the concrete internal pore, producing expansion material and causing expansion stress. When the force is greater than the tensile strength of concrete, it will lead to a significant reduction in concrete strength and even cause damage to the concrete structure.

Upon observation, it was found that there were no signs of corrosion on the surface of the control concrete at the end of the wet and dry cycles, as shown in Figure 18a. However, the specimen doped with blended fibers remained intact as a whole, as shown in Figure 18b.

However, after the specimen was subjected to external force, it was observed that the right side of the specimen was completely peeled off. According to the data in Figure 19, the compressive strength of the control group decreased significantly by 38% compared to the strength before erosion. From Figure 17 it can be seen that there is a layer of sulfuric acid corrosion products on all the surfaces of the fly ash concrete. The cement on the surface of the concrete chemically reacted with Mg^{2+} and SO_4^{2-} to produce calcium alumina as well as gypsum and other substances.



(**a**) (**b**)

Figure 18. Damage morphology diagram after corrosion. (**a**) Control group, (**b**) mixed fibers group.

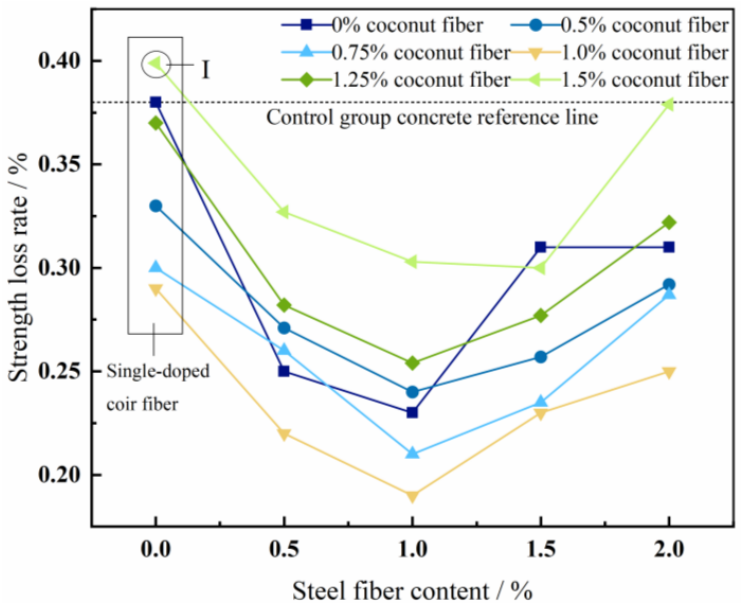


Figure 19. Specimen strength loss rate curve.

The reason for I should be that the single admixture of coconut fiber is too much, as it results in more voids within the matrix. During immersion, the sodium sulfate solution penetrates through these voids into the interior of the concrete. After several cycles of drying and wetting, the degree of corrosion on the matrix intensifies, and this ultimately causes a significant decrease in compressive strength, as shown in Figure 20.



Figure 20. Coconut fiber (1.5%) test block schematic diagram.

Figure 21(I) is a photo of the concrete specimen with coconut fibers, and a large number of holes appear on the surface. The preliminary analysis found that the sulfate related to the internal pores after passing through the lime on the corrosion surface, forming a channel. In the Figure 21(II) group (1.0% steel fiber, 1.0% coconut fiber), a small amount of brown rust spots was found on the surface of the concrete test block. This is due to the precipitation of Fe^{2+} from the surface of the concrete after corrosion. However, these rust spots only appear within the millimeter range of the concrete surface. The internal structure of the concrete still maintains good mechanical properties and durability and there was little effect on the overall structure of the concrete, showing good sulfate resistance. Whether there is a single type of fiber or mixed fibers, this can effectively alleviate the decrease in compressive strength of a concrete matrix after appropriate addition. This is similar to the findings of Paul et al. [38], where the hybrid fibers were able to utilize the bridging effect to improve the durability performance while controlling cracking.



Figure 21. Apparent state photo of specimen after corrosion. (**I**) Single mixed coconut fibers fly ash concrete. (**II**) Mixed fibers group (1.0% steel fibers and 0.5% coconut fibers).

4. Conclusions

To cope with the problems of cracking and spalling of the lining concrete in tunnels in coastal areas due to loading and long-term chemical corrosion, in this study, steel fibers and coconut fibers were introduced in different volume fractions, individually or mixed, into the fly ash concrete matrix. The performance of the hybrid fiber fly ash concrete reinforced with steel fibers and coconut fibers was thoroughly analyzed by carrying out mechanical property tests and durability tests, and the following conclusions were obtained:

- With the admixture of fibers, the mechanical properties of fly ash concrete all showed a trend of first increasing and then decreasing, and the mixed fiber fly ash concrete had better performance compared to the steel fiber concrete and coir fiber concrete. The synergistic effect between the different fibers gave the concrete a better resistance to impact;
- The results of the mechanical properties tests showed that the inclusion of an appropriate amount of fibers can induce the fly ash concrete to change the brittle damage of the matrix into ductile damage at the time of destruction. When the volume admixture of both steel fibers and coconut fibers was 1.0%, the bridging effect of the fibers significantly enhanced the flexural strength of the fly ash concrete. The strength was enhanced by 26.58% compared to the control group;
- The results of the durability tests showed that when steel fibers were mixed with coconut fibers at an equal volume ratio of 1.0%, they not only effectively reduced the diffusion of chloride ions, but also resisted the erosive effect of sulfates to the maximum extent. Using an appropriate amount of fibers can effectively inhibit the extension of concrete cracks, thus preventing the penetration and diffusion of aggressive substances;
- In this study, the key indexes of compressive strength, flexural strength, and resistance to sulphate corrosion in the mix were considered for the tunnel lining environment in coastal areas. The optimal ratio of hybrid fibers in the fly ash concrete used to enhance the comprehensive performance was found through the tests. The durability of the matrix was significantly enhanced while improving the toughness and crack resistance of the concrete. The composite application of steel fibers and coconut fibers can therefore effectively extend the service life of a tunnel lining structure and improve its sustainable utilization.

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