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An experimental model for assessing abrasion and erosion damage of coral concrete under flow conditions

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Abstract: Coral concrete is a structural solution for building breakwaters in coastal areas and offshore islands. However, in the marine environment, this structure is often affected by waves and currents carrying coral sand, causing the structure to gradually abrade and erode, affecting the quality of the project. This study builds a laboratory experimental model with five different ages of coral concrete (1, 3, 7, 14, 28 days) to assess the level of abrasion and erosion. The results show that coral concrete has the same compressive strength with repeated loading as regular concrete, but its resistance to abrasion and erosion is worse. 3D scanning results show that concrete samples under 7 days have relatively profound material loss. At 7 and 28 days, coral concrete lost 22.3% and 15.3% of mass due to abrasion and erosion, respectively, compared to regular concrete. Therefore, it is necessary to improve the abrasion and erosion resistance of coral concrete to ensure the durability and longevity of the structure when constructed on offshore islands.

Keywords: *Abrasion and erosion, Coral concrete, Experimental, Flow.*

1. Introduction

Coral concrete is a special type of concrete that uses sand and coral stone as the primary aggregate. This aggregate is produced from dead natural coral or crushed coral stone, replacing the usual stone aggregate in concrete. Coral concrete is often used to construct works in coastal and island areas. Throughout its history, coral concrete has demonstrated its applicability, mainly since the US military used it during World War II to build structures on islands in the Western Pacific [1]. Ehlert surveyed the quality of coral concrete on Bikini Atoll in the Pacific and concluded that it could maintain its durability after 11–16 years of use [2]. Kishore et al. found that the micro-hardness of the interface transition zone in coral concrete is significantly larger than that of conventional concrete [3].

Bunyamin et al. used fine coral aggregate to replace part of the cement and fine aggregate at a replacement rate of 5%. The test results of the concrete compressive strength performed after 28 days of curing reached 17.01 MPa, compared to the specified compressive strength of the concrete sample of 17 MPa, and the tensile strength of the concrete reached 2.52 MPa [4]. Wattanachai, et al. [5] reported that the diffusion coefficient of chloride ions for coral concrete is higher than that of conventional concrete with the same cement-water ratio [5]. Recent studies in Vietnam have demonstrated that coral concrete has good impact resistance and a high strength level, reaching 30 MPa [6] opening up great potential for construction in offshore island areas where there are many difficulties in materials and high costs in marine transportation.

When constructing sea dike projects in the aquatic environment will disrupt the natural flow process, and the flow will also agitate sand, gravel, and foreign objects in the water, leading to impact and abrasion on the project. Abrasion damage to structures is determined by factors such as

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the size and content of particles in water, flow velocity, flow angle, impact time and concrete quality [7-10]. Figure 1 shows abraded and eroded concrete structures after long exploitation.

Figure 1.
Surface Abrasion and Erosion of Structures on Offshore Islands.

Several testing methods have been developed to determine essential parameters affecting abrasion damage and evaluate the abrasion rate of hydraulic concrete structures. ASTM C418 recommends using Ottawa sand for spraying concrete specimens [11, 12]. However, this type of sand may be too coarse to accurately reflect the actual flow's energy.

A method for assessing the impact of sediment-laden flow has been developed by Liu, et al. [13] and Liu, et al. [14]. Abrasive particles, mainly sand, are mixed with water to form a sediment-laden flow, which impacts the concrete surface at a certain speed. The size of the abrasive particles, density, hardness, and impact angle significantly affect the abrasion damage on the concrete surface. Liu, et al. [13] also found that increasing the size of the abrasive particles increases the abrasion rate because small particles are less likely to cause dangerous cracks on the surface. In addition, the damage increases as the density of sand in the abrasive increases. The flow exerts a compressive and pushing action on the material, causing tensile (horizontal) stresses at the surface of the concrete structure. Tensile stress is the leading cause of the formation and development of cracks at the transition zone between cement stone and aggregate, eventually leading to abrasion and erosion.

In Vietnam, research on concrete's abrasion and erosion resistance, generally and coral concrete, in particular, is minimal. Therefore, this study aims to develop an experimental model to evaluate the abrasion and erosion level of coral concrete and investigate the effect of curing time on abrasion and erosion resistance. The time points selected for evaluation include 1 day, 3 days, 7 days, 14 days and 28 days after pouring the sample. This approach allows us to observe and analyze the change in abrasion and erosion resistance over time, thereby identifying the stages when the concrete may be most vulnerable.

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2. Mechanism of Abrasion and Erosion of Coral Concrete

The abrasion of concrete mainly comes from mechanical impact [15]. A common approach is classifying abrasive particles into two main groups: suspended and bottom particles. Under the influence of water flow, both types of particles contribute to the erosion of the surface of hydraulic structures, leading to peeling off the concrete surface. Initially, the abrasion occurs relatively uniformly, but over time, due to the heterogeneity of the concrete, uneven wear pits gradually appear under the influence of continuous flow [15, 16].

The appearance of abrasion pits can disrupt the flow, creating eddies. These eddies not only reduce local pressure but also form stronger impact forces due to the impact of the surrounding water mass, thereby accelerating the destruction of the structure's surface. For concrete, the wear mechanism usually occurs in a cycle: pit formation, flattening of protrusions, peeling off of surface layers, and, in many cases, combined with erosion, which makes the damage more severe (the process is shown in Figure 2, [16])

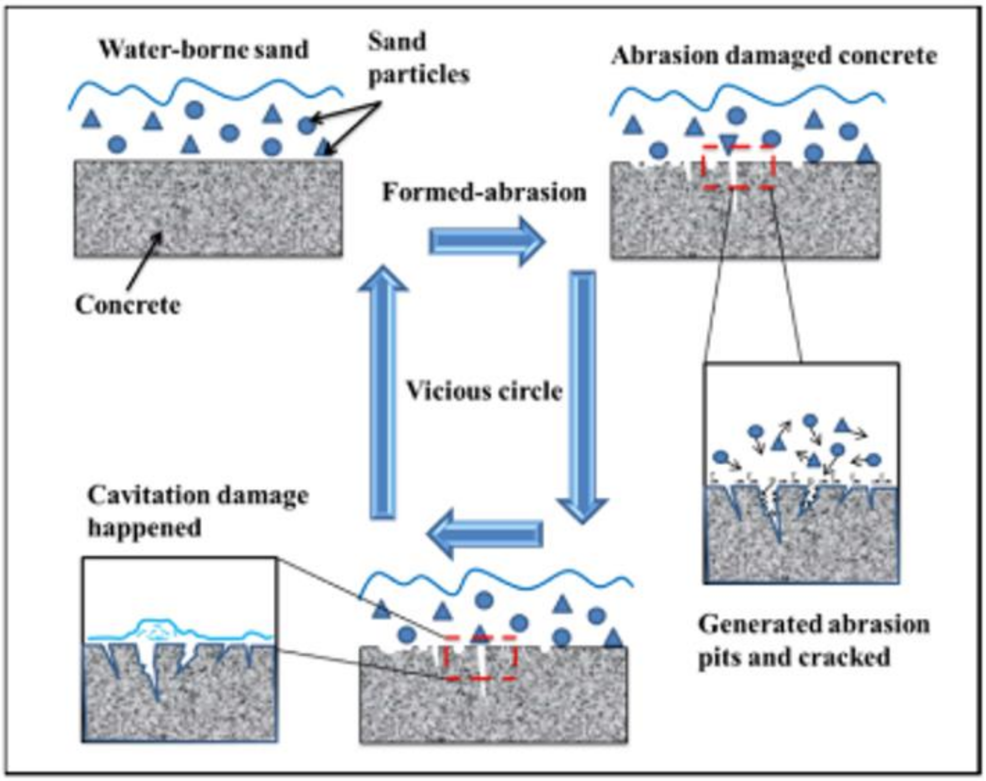

Figure 2.
The Process of Damage due to Abrasion and Erosion for Concrete Structures Surface.
Source: Guo, et al. [16]

In addition, the type of abrasive particles also significantly influences the degree of structural deterioration. Typically, wear caused by bottom particles tends to cause more obvious damage than that caused by suspended particles. Bottom particles are usually larger, creating higher local stresses when colliding with the concrete surface. As a result, cracks expand faster, and after repeated impacts, the structure is at risk of structural deterioration when the material strength reaches its endurance limit [17, 18].

Usually, breakwaters on offshore islands are mainly constructed using the in-situ concrete pouring method. The construction process often includes many steps to ensure the stability of the structure against the impact of the harsh marine environment. First, to facilitate construction, the construction unit builds a temporary cofferdam. The cofferdam is a barrier to prevent sea waves from directly impacting the construction area, creating a stable environment for pouring concrete and installing components. This is especially important in offshore construction conditions, where strong winds and waves can erode materials or make pouring and maintaining concrete difficult. After completing the cofferdam, essential parts of the breakwater are constructed, including wave deflectors and tray feet. The wave deflector is one of the critical components, helping to reduce the energy of waves when they hit the structure, thereby limiting the impact of erosion. Meanwhile, the tray foot plays a role in stabilising the foundation of the breakwater, preventing erosion of the structure's foot due to the continuous impact of currents and wave forces.

However, a notable point in this construction method is the relatively early dismantling time of the cofferdam. When the concrete of the wave deflector and tray foot structures has just reached the age of about 1 to 3 days - that is, still in the early stages of strength development - the cofferdam has begun to be dismantled. The filling material from the cofferdam is then reused to fill and construct the slope, helping to optimize resources and reduce material transportation costs. However, early dismantling means the concrete structures have not yet reached optimal strength and must be directly exposed to the marine environment. Under the impact of strong sea waves, the wave-absorbing tooth and tray foot structures are at risk of being affected right from the beginning. When the concrete strength is not large enough, the ability to withstand the impact force of waves and currents is limited. In addition, sand particles and suspended materials in seawater can cause abrasion and erosion, reducing the surface quality of concrete over time, as shown in Figure 3.

Figure 3.
The Slope of the Breakwater is Prone to Abrasion and Erosion after Construction.

3. Experimental Model to Determine the Level of Abrasion and Erosion of Coral Concrete Under the Effect of Flow

To study the damage caused by abrasion and erosion of coral concrete samples when exposed to sediment-containing flow (coral sand), a homemade test set was established based on the research idea of Liu and colleagues [19] as shown in Figure 4. The impact experiments of the flow containing coral sediment aim to simulate the damage process caused by abrasion and erosion of coral concrete

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structures, in which sediment particles (coral sand) are transported by water.

The experimental equipment includes a container with dimensions of 1.5 x 1.0 x 1.0m, a main pump (submersible pump for continuous circulation containing coral sand sediment), and a stand for installing concrete samples. During the experiment, a pump continuously stirs the coral sand in the container to prevent it from settling and ensure even distribution during operation, helping it mix well with water. The bracket for installing concrete samples can adjust the tilt angle and height.

Figure 4.
Homemade Experimental Equipment for Determining Abrasion and Erosion Levels.

Due to the characteristics of coral aggregates with irregular shapes, rough surfaces, and many voids, the theory of designing powder-rich concrete and high-strength concrete suggests a higher proportion of binder material, a significant proportion of sand, and the bulk volume method for creating the mix ratio of coral concrete [20]. Coral concrete is designed with a strength grade of C30, and the water-cement ratio is 0.62. The composition mix is shown in Table 1.

Table 1.
Mix Composition of C30 Coral Concrete

Cement	Seawater	Coral sand	Coral rock 1x2	Water - cement ratio (W/C)
kg	kg	kg	kg	0.62
450	279	754	745	
%	%	%	%	
20.20	12.52	33.84	33.44	

Based on the analysis of the abrasion and erosion mechanisms of coral concrete discussed above, and considering the experimental conditions in the laboratory, this paper focuses solely on investigating the abrasion and erosion levels of coral concrete samples at different ages (1, 3, 7, 14, and 28 days). Other studies have considered the influence of flow velocity, water jet angle, and distance from the water jet to the coral concrete surface.

Five concrete panels measuring 15 x 15 x h (where h = 5.5÷7 cm) were cast and used to conduct experiments to assess the level of damage due to abrasion and erosion. In addition, four concrete samples measuring 10 x 10 x 10 cm were cast to measure the 28-day concrete strength.

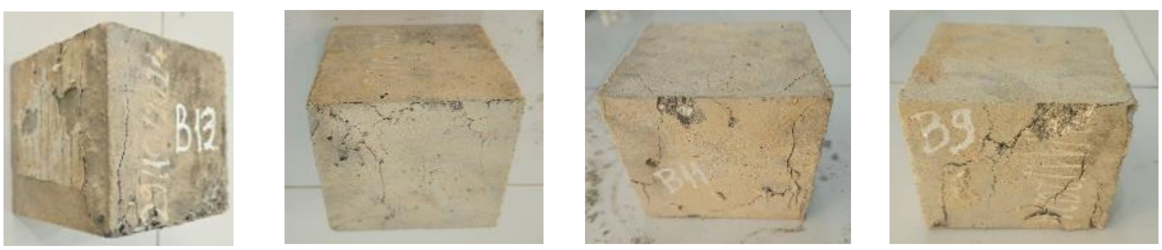
After the coral concrete samples are cast, wait for the samples to reach the strength corresponding to different ages. Then, use the 3-axis rock compression machine to determine the sample's compressive strength.

4. Experimental Results and Discussions

4.1. Compression Test Results of Coral Concrete Samples with Different Numbers of Loading Cycles

Structural components in offshore island constructions are commonly exposed to cyclic wave-induced loading. Therefore, in this study, the authors conducted compression tests on four samples subjected to static cyclic loading with different numbers of cycles (non-cyclic, five cycles, 10 cycles, and 19 cycles). The stress range of the cyclic loading varied from 40% to 80% of the maximum compressive strength (corresponding to 12 MPa to 24 MPa). This cyclic loading amplitude was adopted based on the study by Andrawes [21]. After the cyclic loading phase, each sample was loaded monotonically until failure. Figure 5 illustrates the different failure patterns of the samples. The crack characteristics of the samples are as follows:

- Sample C1 (non-cyclic) and C2 (05 cycles): Cracks propagate vertically with minimal branching;
- Sample C3 (10 cycles): Cracks begin to show slight branching;
- Sample C4 (19 cycles): Wider crack distribution with interconnected branches.



a. Sample C1 – Non-cyclic | b. Sample C2 – 05 cycles | c. Sample C3 – 10 cycles | d. Sample C4 – 19 cycles

Figure 5.
Damage Shape of Samples during Compression Testing with Different Numbers of Loading Cycles.

The stress-strain diagram of four coral concrete samples clearly shows the influence of cyclic loading on the material's compressive strength (Figure 6). In sample C1 (not subjected to cyclic loading), the failure stress reaches the highest value of 37.22 MPa. When the number of cycles increases to 5 cycles (sample C2) and 10 cycles (sample C3), the failure stress gradually decreases and drops to 34.53 MPa, corresponding to a decrease of 7.2%. Notably, the failure stress did not decrease linearly when loading cycles increased from 10 to 19 (sample C4). Still, it reached a failure value of 35.48 MPa, corresponding to a decrease of only 4.7%. This shows that the strength of coral concrete does not decrease proportionally to the number of loading cycles, but shows a nonlinear damage mechanism. This mechanism mainly originates from the brittle failure state, gradually changing to plastic failure, and the development of local plastic zones inside the concrete structure when the porosity increases [22]. Under the effect of repeated loading, microcracks at the interface between the aggregate and the cement paste tend to spread, leading to local loss of mechanical bonds, causing the overall strength to decrease. However, after a certain number of cycles, the failure reaches a stable threshold at some points in the structure, causing the rate of decrease in the failure stress to slow, as seen in sample C4. On the other hand, due to the small number of test samples and the high heterogeneity of coral concrete, especially the variation in size, shape and strength of coral aggregate, it leads to unstable mechanical behavior under cyclic loading.

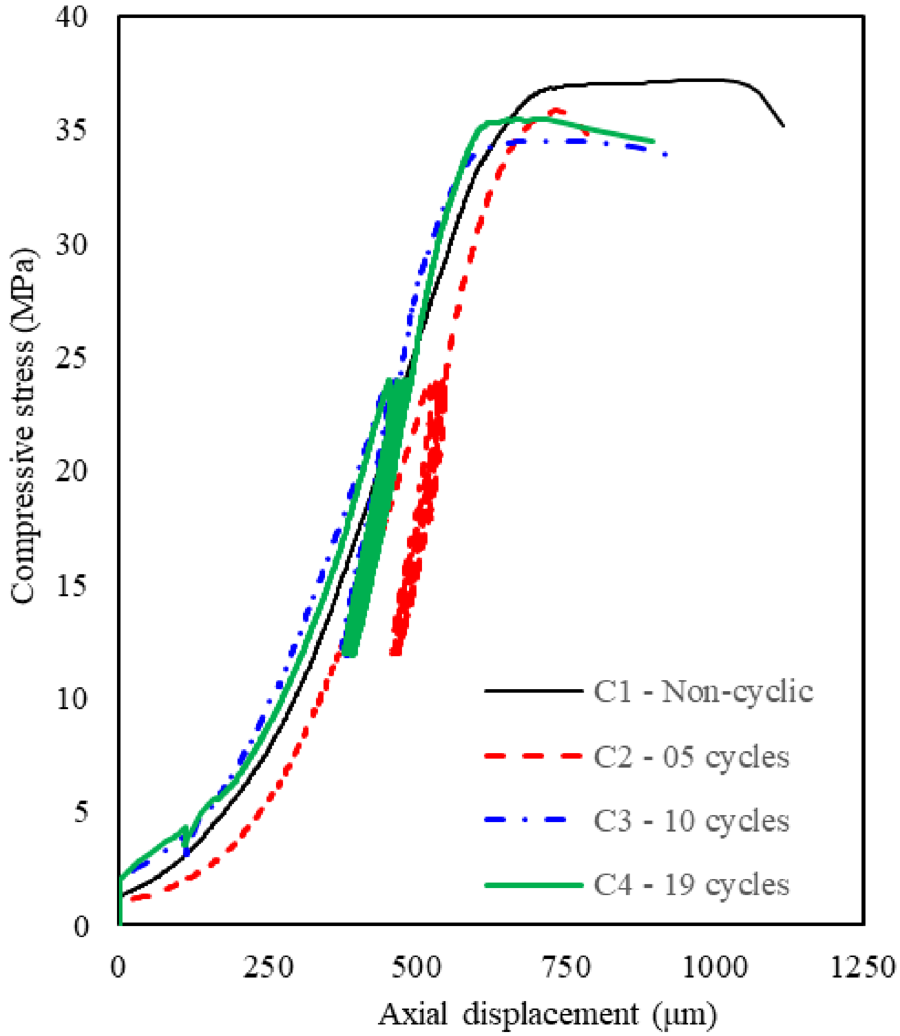


Figure 6.
Stress-Axial Displacement Relationship of the Coral Concrete Samples with Different Numbers of Loading Cycles.

In summary, within the scope of this study (with a maximum of 19 loading cycles), coral concrete shows a maximum compressive strength reduction of about 7.2%. The lowest strength was observed in sample C3, which reached 34.53 MPa. When converted to the standard cube size of 150 × 150 × 150 mm using a correction factor of 0.95 (by TCVN 3118:2022 [23] the standard compressive strength is calculated as 32.80 MPa. Based on the mix design shown in Table 1, coral concrete satisfies and exceeds the requirements for grade C30 concrete (strength ≥ 30 MPa). This confirms the feasibility of using coral aggregates to produce structural concrete that meets technical requirements for compressive strength and durability under static and cyclic loading.

4.2. Results of Evaluating the Level of Abrasion and Erosion of Coral Concrete Samples

The research team conducted experiments on 15 x 15 x h (cm) concrete samples to evaluate the abrasion and erosion of coral concrete at different ages. The concrete samples were fixed on the sample holder, and the sediment-containing flow directly impacted the sample surface, as shown in Figure 7.

a. Experimental preparation

b. Water jet acting on the sample

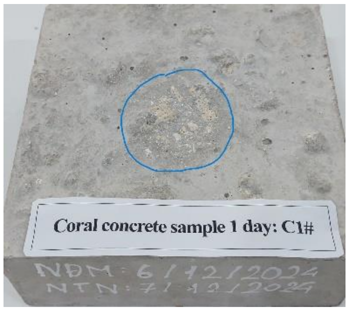
Figure 7.
The Process of Abrasion and Erosion of Coral Concrete Samples.

Building on the research results of Liu and colleagues Liu, et al. [19] the experiments in this paper were conducted with the flow impact time on each concrete slab being 9 hours, the flow velocity being 16.04 m/s, the water jet angle being 90 degrees, and the water jet distance to the concrete surface being 30 cm (the parameters are listed in Table 2). The position of the water jet is at the center of the sample. Before and after each abrasion and erosion test, the sample was weighed to determine the mass loss of the coral concrete.

Table 2.
Experimental Parameters to Assess the Level of Abrasion and Erosion.

Sample	Coral concrete at different ages (days)	Experimental time Liu, et al. [19] (h)	Sand content Liu, et al. [19] (kg/m^3)	Flow velocity Liu, et al. [19] (m/s)	Water jet angle Liu, et al. [19] (°)	Water jet distance to concrete surface Liu, et al. [19] (cm)
C1#	1	9	160	16.04	90	30
C3#	3					
C7#	7					
C14#	14					
C28#	28					

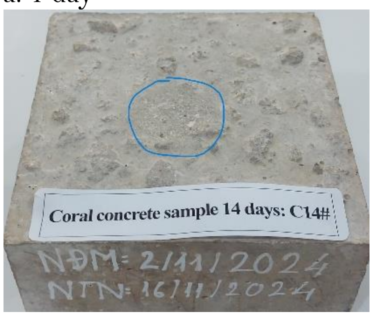
From the actual experimental conditions, the paper only tested the damage caused by abrasion and erosion concentrated at the middle position of the concrete slab (the position directly affected by the flow). At that time, the average height of the outer surface was not damaged by abrasion and erosion, and was taken as a reference to determine the abrasion depth of the concrete samples after the test. The image after the abrasion and erosion test of samples C1#, C3#, C7#, C14# and C28#, when the samples have reached sufficient strength according to their age, is shown in Figure 8.



a. 1 day

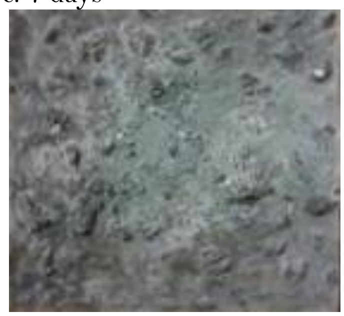
b. 3 days

c. 7 days



d. 14 days

e. 28 days after the experimental



f. 28 days before the experimental

Figure 8.
Level of Abrasion and Erosion on the Surface of Coral Concrete Samples after Experimentation.

Under the impact of currents, all coral concrete samples tend to suffer surface damage, with the abrasion and erosion range extending from the center of the test sample to the surrounding area. Surface damage to concrete samples is particularly evident in low-age samples (1 to 7 days) due to the incomplete bonding system of aggregate particles, reducing their resistance to mechanical impact (Figures 8a, b, c). Surface deterioration mainly appears as localized flaking in the area directly affected by the flow, with the highest local stress. The abrasive and erosive action caused by the movement of sand particles in water weakens the surface structure, reduces the strength of the concrete, and promotes the formation of cracks, leading to an increase in the extent and depth of abrasion and erosion over time, especially in low-age concrete samples. The deterioration process starts from the center and spreads outward, influenced by intrinsic properties such as porosity and heterogeneity of the material. These factors accelerate mechanical deterioration and the degradation of concrete surfaces under the influence of flow, directly affecting coral concrete's durability and service life in hydrodynamic environments.

To accurately assess the extent of material loss caused by abrasion and erosion after 9 hours of testing, coral concrete samples were weighed before and after testing at various concrete ages. The data illustrating the material loss on coral concrete samples is presented in Figure 9.

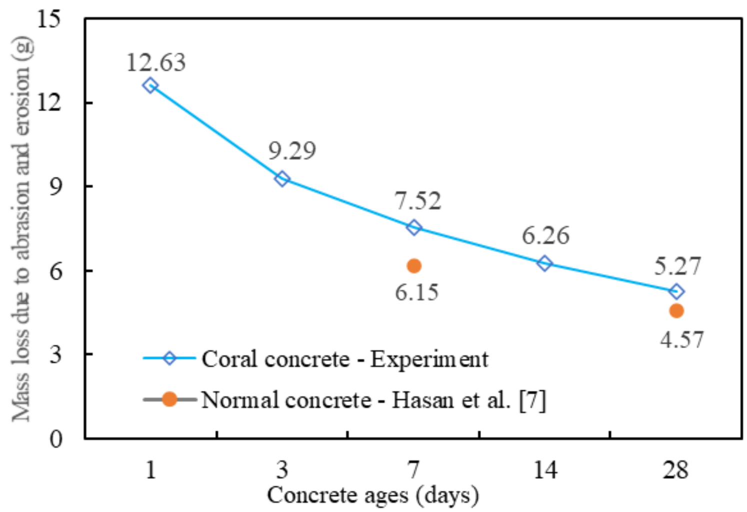


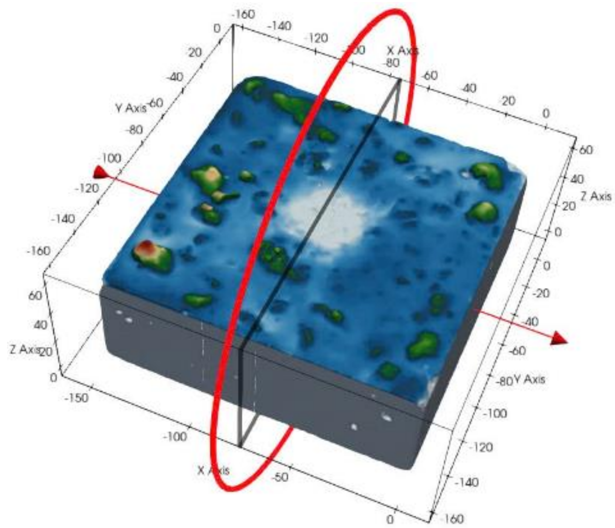
Figure 9.
Abrasion and Erosion Losses of Coral Concrete Samples at Different Ages.

The experimental results show that coral concrete at 1 to 7 days experiences significantly more material loss than samples at 14 to 28 days. This indicates a clear difference in concrete's abrasion and erosion resistance over the setting and curing time. As the concrete strength increases with age, the loss due to abrasion and erosion tends to decrease, demonstrating an improvement in coral concrete's abrasion and erosion resistance. For concrete samples under 7 days old, the cement paste content in the surface layer acts as a temporary protective layer for the aggregate against direct abrasion and erosion. However, once this paste layer is compromised, the abrasion and erosion rate depends on the resistance of the aggregate itself. Due to their porous and brittle properties, coral aggregates are more vulnerable to impact when exposed, leading to an increased material loss rate.

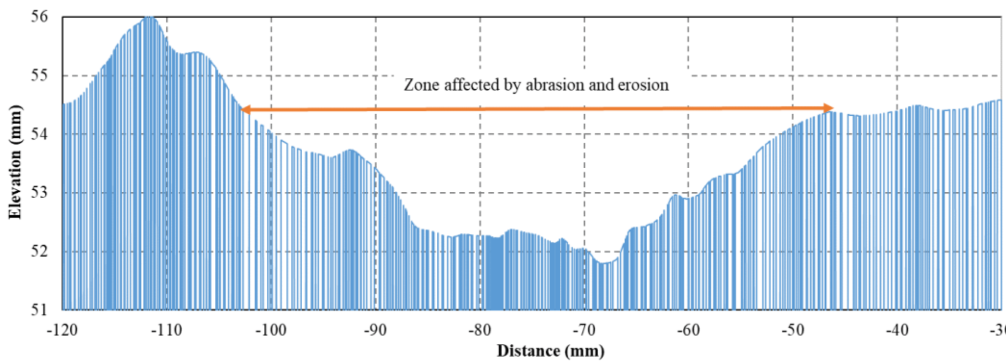
Furthermore, for concrete samples aged 7 days and beyond, the mass loss gradually decreases and follows a more linear trend, in contrast to the period from 1 to 7 days, which exhibits a nonlinear relationship and significant fluctuations in mass loss. Based on the analysis, early-stage strength development is crucial in enhancing coral concrete's abrasion and erosion resistance.

Compared with the research results of Hasan, et al. [7] it was found that at the same time points of 7 days and 28 days, coral concrete lost 22.3% and 15.3% of its mass, respectively, compared to conventional concrete. This reflects the limited abrasion and erosion resistance of coral concrete, although the compressive strength of the samples still meets technical requirements. This result highlights the need for further research to enhance coral concrete's abrasion and erosion resistance mechanism for its application in designing structural components for works in offshore island areas.

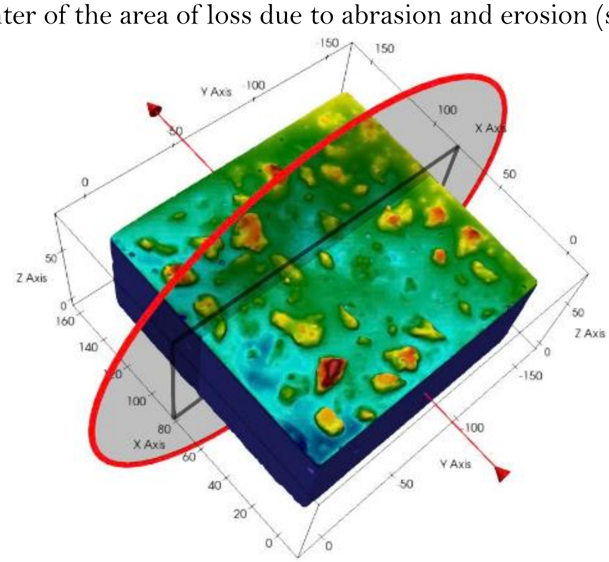
To clarify the characteristics of the loss area due to abrasion and erosion on the surface of coral concrete, the group of authors used KSCAN Magic 3D Scanner to scan two test specimens, C3# and C7#, after the end of the experiment. The analysis results from the scanned data clearly show the morphology and level of surface loss of coral concrete under the combined effects of abrasion and erosion. Figures 10a and 10c show that in the central area, which is directly affected by the continuous flow, a concave area appears larger than the surrounding areas that are less affected. This concave area represents a significant material loss due to the cumulative abrasion and erosion. The elongated concave shape of the loss area shows that the damage process did not occur suddenly but resulted from the accumulation over many load cycles and the continuous erosion of the flow containing coral sand. With the characteristics of coral concrete – using aggregates with a natural porous structure, large voids and weaker bonds than traditional concrete – the abrasion and erosion phenomenon becomes more severe, as shown in Figure 9. The large amplitude of the cross-section and the apparent unevenness shown on the 3D surface model also demonstrate this loss characteristic.



a. 3D cross-section of sample C3#



b. Cross-section at the center of the area of loss due to abrasion and erosion (sample C3#)



c. 3D cross-section of sample C7#

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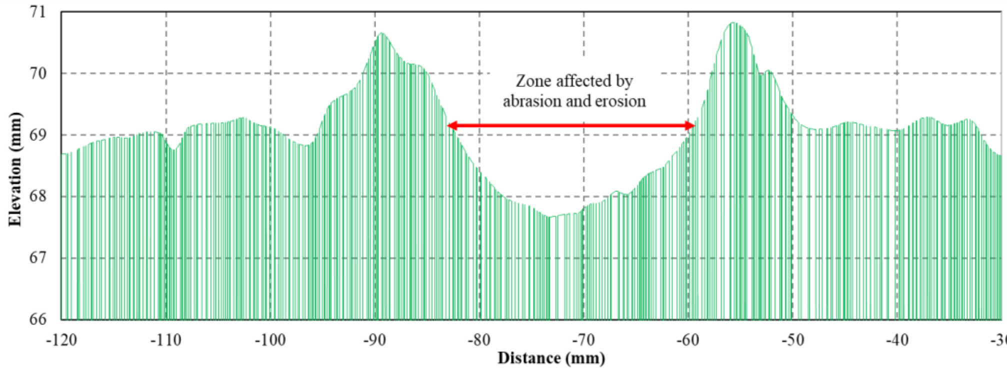

d. Cross-section at the center of the area of loss due to abrasion and erosion (sample C7#)

Figure 10.
CT Scan of the Experimental Sample Using the KSCAN Magic 3D Scanner.

Under the combined impact of continuous flow carrying coral sand particles, the two test samples C3# and C7# showed different levels of surface loss, reflecting a clear difference in erosion resistance. Specifically, according to Figure 10b, sample C3# recorded a loss zone extending from about -102 mm to -47 mm, with the cross-sectional depth decreasing from 54.5 mm to 52 mm, indicating significant material loss. Meanwhile, Figure 10d shows that sample C7# only suffered damage in a narrower range, from -83 mm to -60 mm, with a slight decrease in depth from 69.2 mm to 67.8 mm.

This difference mainly stems from the degree of concrete strength development at different ages. Sample C3# at 3 days of age is still in the early stage of hydration, when the structure is not yet stable, the density is low, and the bond between aggregate particles is not strong enough. This reduces the resistance to mechanical impact and erosion of the flow, leading to a wide range of damage and high material loss. In contrast, sample C7# at 7 days has undergone a longer hydration process, forming a tightly bonded network between aggregate particles and binder. The material structure becomes more stable, significantly improving resistance to abrasion and erosion under the continuous effect of flow. These results show that curing time is decisive in developing coral concrete's mechanical strength and resistance to abrasion and erosion, especially in complex, dynamic and hydraulic environments.

5. Conclusion

The paper conducted an experimental evaluation of the compressive strength under repeated loading, abrasion and erosion resistance of coral concrete over the curing time and drew the following conclusions:

Under the impact of repeated loading, the compressive strength of coral concrete tends to decrease, but not according to a linear law. This result is due to the heterogeneity of coral concrete and the limited number of test samples. When the number of cycles increases, the failure stress value does not decrease evenly, indicating a nonlinear failure mechanism, shifting from brittle to ductile failure.

The abrasion and erosion resistance of coral concrete samples from 1 to 7 days is more vulnerable due to the weak bond structure. Meanwhile, samples from 14 days and above significantly improve abrasion and erosion resistance. The abrasion and erosion phenomenon is mainly concentrated in the area directly affected by the flow, manifested by the peeling of the surface layer and the reduction of material volume. This degradation progresses in a nonlinear trend in the first 7 days, then stabilises and becomes almost linear from the 14th day. When the cement slurry layer is abraded, the exposed coral aggregate increases the risk of material loss due to the combined effects of abrasion and erosion.

The 3D scanning results after the abrasion and erosion test showed that the coral concrete sample C3# suffered more serious material loss than the C7# sample. This difference reflects the critical role of maintenance work in protecting coral concrete, such as extending the curing time, applying a protective coating, or using additives to improve the mechanical properties of concrete. Enhancing coral concrete's abrasion and erosion resistance is necessary for application in marine environments and offshore island areas.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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