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Cover page

This report is one of the three deliverables of work package 15 bioreceptive cement (D15.1 Bioreceptive cement) in the DuneFront project, aiming to design and implement a new eco-dike prototype that integrates nature-based solutions with hard infrastructure. The project focuses on creating biodiverse, resilient, and aesthetically pleasing coastal defenses using innovative materials like bioreceptive cement.

The report evaluates various bioreceptive cement formulations, including CEM III-B, Magnesium Phosphate Cement (MPC), Bone Ash Mixes, Foamed Concrete, and CEM II/A-LL, for their effectiveness in supporting biological growth, mainly Marram grass. It investigates how surface texture and pH reduction influence seed germination and plant development, focusing on optimizing these materials for use in eco-dikes.

Policy and Societal Contribution: Developing bioreceptive types of cement contributes to sustainability in coastal protection. By promoting biodiversity and stabilizing sandy environments, these materials help mitigate erosion and enhance ecosystem resilience. The findings could influence policy recommendations around adopting eco-dike systems in coastal management.

Policy Recommendations: To further integrate nature-based solutions in coastal defense, it is recommended that governments and environmental agencies adopt policies supporting the use of bioreceptive materials in construction. This would foster ecological stability and long-term sustainability in coastal zones, addressing climate change challenges such as rising sea levels and increased storm surges. Additionally, incentives for research and development into sustainable construction materials should be prioritized.

Table of Content

Table of Figures

Table of Tables

List of abbreviations

Abbreviation	Explanation
WP	Work package
D	Deliverable
MPC	Magnesium Phosphate Cement
BA	Bone Ash
VMA	Viscosity Modifying Admixtures
ADP	Ammonium Dihydrogen Phosphate
MgO	Magnesium Oxide
NaOH	Sodium Hydroxide,
KOH	Potassium Hydroxide
$Ca(OH)_2$	Calcium Hydroxide

1. Overview

1.1 Introduction

1.1.1 Overview of work package 15 (WP15- Co-creation of a new eco-dike prototype)

Work package 15 aims to design and implement an eco-dike prototype that integrates nature-based solutions with hard infrastructure. The key focus is on creating a biodiverse, resilient, and aesthetically appealing structure through innovative materials and stakeholder-driven processes.

1.1.2 Tasks of Work Package 15

The first major task within WP15 is the development of bioreceptive cement (Task 15.1). This involves creating cementitious materials with optimized properties, such as low pH, increased porosity, and enhanced surface roughness to support biological growth. Various mixtures, including magnesium phosphate cement and bone ash, are being evaluated for their bioreceptivity, structural integrity, and suitability for 3D printing. The goal is to ensure the material is functional and conducive to fostering biodiversity on the eco-dike's surface.

Another critical aspect is the realization of complex geometries for eco-dikes through 3D printing technology (task 15.2). This task focuses on designing forms that enhance resilience and biodiversity by enabling wind-driven sand trapping and supporting the establishment of vegetation. These geometries will also improve the structure's visual appeal, aligning ecological functionality with aesthetic considerations.

Stakeholder co-creation is significant in WP15 (task 15.3), emphasizing collaborative engagement with local stakeholders to shape the project. This involves multiple co-creation sessions to gather input on design priorities, ecological goals, and the overall vision for the project areas. The process ensures that the eco-dike aligns with local needs, addressing social, ecological, and aesthetic concerns.

Finally, the WP includes the preliminary design and implementation of the eco-dike prototype (15.4). This involves developing technical designs, securing permits, and planning the construction, monitoring, and maintenance of the structure. These steps aim to ensure that the final prototype is not only technically and ecologically viable but also ready for practical application in coastal defense.

1.1.3 Milestone and deliverable of work package 15

WP15 has several key milestones that mark its progress toward the eco-creation and implementation of the eco-dike prototype. The first milestone is the finalization of the bioreceptive cement mixture, targeted for April 2025. This will ensure that suitable material is available for further development and integration into the eco-dike design. Another milestone is completing all co-creation sessions by April 2025, culminating in a clear and stakeholder-informed vision for the project. The technical design phase, including permitting, is expected to begin following April 2025, setting the foundation for prototype construction.

These milestones reflect critical junctures in the project's timeline, ensuring the integration of innovative material science, stakeholder insights, and technical precision to deliver a functional and sustainable prototype.

1.2 Aims and objectives of this report.

This report evaluates various cementitious materials, including CEM III-B, Magnesium Phosphate Cement (MPC), Bone Ash Mixes, and Foamed Concrete, to determine their effectiveness in fostering plant growth, especially Marram grass (*Ammophila arenaria*). The tests focus on these materials' physical, chemical, and biological properties, including their impact on seed germination and seedling growth. The report also investigates the effects of pH levels and surface roughness on the biological compatibility of these materials, providing insights into how cement mixtures can be optimized for environmental and ecological applications.

2. Bioreceptive cement development

2.1 Low pH cement mixtures

The development of low-pH cementitious materials was thought to play a critical role in enhancing bioreceptivity by creating an environment conducive to biological growth while maintaining structural stability. The primary focus was on the following binder types:

2.1.1 CEM III-B

These cements are recognized for their high slag content (66-80%), which significantly reduces the pH of the material, making it suitable for bioreceptive applications. These cements exhibit enhanced resistance to sulfate and chloride attacks, making them highly durable in coastal and marine environments. (Manso et al., 2014).

2.1.2 CEM II/A-LL

CEM II/A-LL is a Portland composite cement with 6-20% fine high-purity limestone replacing a portion of clinker. This partial substitution reduces the carbon footprint while maintaining comparable mechanical and durability properties to CEM I. The inclusion of limestone enhances workability and results in a lighter color, making it ideal for structural and architectural applications. Its setting times and performance in resistance to carbonation and chloride ingress are on par with traditional cement, ensuring suitability for general construction and precast concrete products. The environmental advantages and versatility of CEM II/A-LL make it an excellent choice for low-carbon, sustainable building projects. (Lothenbach et al., 2008), (Limbachiya et al., 2014).

2.1.3 Magnesium phosphate cement (MPC)

These cements, known for their rapid setting time and low pH (5.8-7), faced workability challenges during initial testing. Adjustments, including the addition of borax and modification to water-cement ratios, improved setting times and flowability. However, the high cost and handling challenges of MPC ingredients were notable limitations. It has been tried to replace the binder with Ammonium Dihydrogen Phosphate (ADP, $NH_4H_2PO_4$) and Magnesium oxide (MgO), maintaining an ADP:MgO ratio of 1:1.75 (Manso et al., 2014).

2.1.4 Bone ash cement

Bone ash, a phosphorous-rich material, was partially replaced to replace the binder to improve bio-receptivity; increasing bone ash content led to decreased compressive strength and viscosity challenges. Tests described in the literature showed that up to 30% of replacements maintained acceptable workability and strength. (Falade et al., 2012). Different amounts of bone ash have been investigated, from 10%, 30%, to 50% replacement of the binder content, and these series are labeled as *"10% BA," "30% BA,"* and *"50% BA"* in Table 1.

2.1.5 Foamed concrete

This mix, characterized by high porosity, demonstrated potential for enhanced bioreceptivity but showed reduced mechanical strength. Adjustments to foam admixtures can improve printability. (Zhang & Sanjayan, 2024), (Pasupathy et al., 2022).

Table 1: Mix options to increase bioreceptivity (kg/m^3)

(kg/m^3)	CEM III/B 42.5	MPC_3	10% BA	30% BA	50% BA	Foam	CEM II/A-LL 42.5
CEM III/B 42,5	471.5	235.8	448	401	354	471.5	-
CEM II/A-LL	-	-	-	-	-	-	900
Slag	471.5	235.8	448	401	354	471.5	-
Sand	943	943	943	943	943	943	900
Superplasticizer	0.94	0.94	0.94	0.94	0.94	0.94	0.94
VMA*	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Water	330	330	330	330	330	297	315
MgO	-	600	-	-	-	-	-
ADP, $NH_4H_2PO_4$	-	343	-	-	-	-	-
Bone ash	-	-	47.2	142	236	-	-
Foam admixture	-	-	-	-	-	33	-

*Viscosity-modifying admixtures

2.2 Integration of Bioreceptive Properties

Enhancing bioreceptivity involves integrating design and material science to support biological growth. Testing focused on the species used and the properties of the surface.

2.2.1 Biological compatibility

Marram grass (*Ammophila arenaria*) is a robust species suitable for eco-dike stabilization due to its tolerance to high salinity and wind stress. However, germination studies reveal sensitivity to burial depths. (Lammers et al., 2024) Highlighting the need to design substrate layers in eco-dikes carefully. The grass thrives in well-drained, sandy soils with pH values ranging from 4.5 to 9.0. By integrating marram grass into an eco-dike prototype, sand deposition can be naturally stimulated, promoting dune formation and further stabilization (Gadgil, 2002), (*Ammoare.Pdf*, n.d.).

2.2.2 Surface treatment and porosity

Surface roughness and porosity were optimized to support the germination and adhesion of biological organisms. Preliminary experiments demonstrated the potential of marram grass and algae colonization under controlled conditions.

2.3 Testing procedures

Testing procedures for bioreceptive cement were designed to evaluate the compatibility of different formulations (see Table 1) with biological growth while ensuring mechanical and chemical performance in marine and coastal environments.

Mortar mixtures were cast into molds (e.g., 4x4x16 cm^3) to form standard test specimens with a triple replicate for each mix. For mechanical property testing, the molds were designed for bending and compressive strength tests according to the EN 196 standard.

The samples were cured under standard conditions at 20 ± 2°C and 95% relative humidity for 28 days, according to the EN 196 standard. In some tests, accelerated carbonation (in a chamber with 3% CO2 for one week) was performed to mimic the effect of carbonation in marine and coastal environments.

Mechanical and biological testing was performed after 28 days of curing for mechanical property tests and at later stages for biological testing.

2.3.1 pH optimization

Fresh mortar typically has a high pH, deterring biological colonization. Tests were conducted to measure:

- Initial pH: Immediately after curing, identify formulations with naturally low pH levels.
- pH compatibility range: evaluated against target organisms (marram grass seeds) to ensure suitability for biological colonization.

2.3.2 Mechanical property testing

Compressive Strength Testing: According to EN 196, compressive strength was tested after 28 days of curing. Samples were subjected to a compression test, and the results were recorded. The strength values were compared across different cement mixtures.

Bending Strength Testing: Bending tests were also conducted per EN 196 standards to assess the samples' flexural strength.

2.3.3 Biological Growth Experiments

Seed Germination Tests: *Ammophila arenaria* (marram grass) seeds were used to evaluate the bioreceptivity of the cement mixtures. The seeds were planted on cement samples at varying burial depths (e.g., in holes 1.5 cm deep in the first setup and on top of the mortar surface in the second setup). After planting, a thin layer of sand (approximately 1–2 mm) was applied over the seeds. This additional layer of sand helps simulate the natural conditions of dunes by promoting moisture retention and preventing rapid drying,

- First setup: The germination tests were conducted to assess the growth potential of marram grass using mortar prisms. Four holes (1.5 cm deep and spaced 1.5 cm apart) were drilled into each sample (see Figure 1). However, some samples cracked, so not all had the intended four holes. After drilling, four marram grass seeds were carefully placed into each hole and covered with a thin layer of sand to keep them in place during watering. The sand was sourced from the Belgian coast. The seeds were watered lightly, just enough to keep them moist without causing waterlogging. The samples were kept under controlled day/night conditions, exposing them to light from 5 a.m. to 8 p.m., with regular watering when the sand appeared dry.

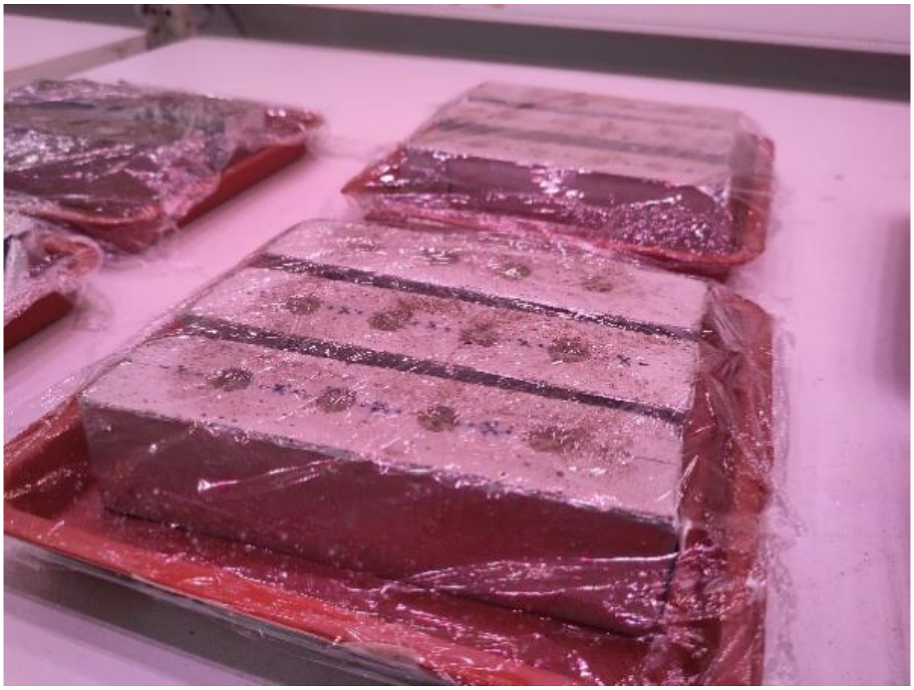

Figure 1: Samples with drilled holes for germination test

Figure 2: Samples for germination test in larger containers

- **New Setup**: This setup was to refine our germination setup (see Figure 2), where the concrete samples were placed in larger containers filled with sand and covered with an additional 1-2 mm of sand to enhance moisture retention. The seeds (6 per sample) were then buried in this layer, replicating conditions that promote optimal germination. The mortar samples with seeds were placed in controlled environments (day/night cycles with light provided from 5 am to 8 pm) with moisture maintained to encourage germination. Germination was monitored over 20 days, and seedling growth was recorded. Three control groups were included: one with only sand, one with a sand-soil mixture, and the other with plastic to recreate the concrete surface to test whether the marram grass roots can adapt to obstacles. Additionally, this setup was used to test if the seeds would germinate better without an alkaline material like mortar by comparing germination rates and growth in sand-only conditions.

Surface Roughness Influence: A surface roughness test was conducted to evaluate the ecological compatibility of the materials further. This involved preparing concrete samples with varying aggregate sizes: coarse (8-20 mm), medium (2-8 mm), and sand (0-4 mm) (see Table 2 & Figure 3(a)). The binder used was CEM II/A-LL 42.5N with a water-to-cement ratio of 0.5, which was poured over the aggregates as a second step (Figure 3(b)). Samples were compacted using vibration (Figure 3(c)) and divided into two sets: one was tested after one week of curing at 95% humidity, and the other was carbonated for another week to lower the pH. Ten marram grass seeds were placed on these surfaces and covered with 100 g of sand per container, and their germination was observed. The rough surfaces provided additional texture, which helped retain moisture and stabilize seeds during windy days.

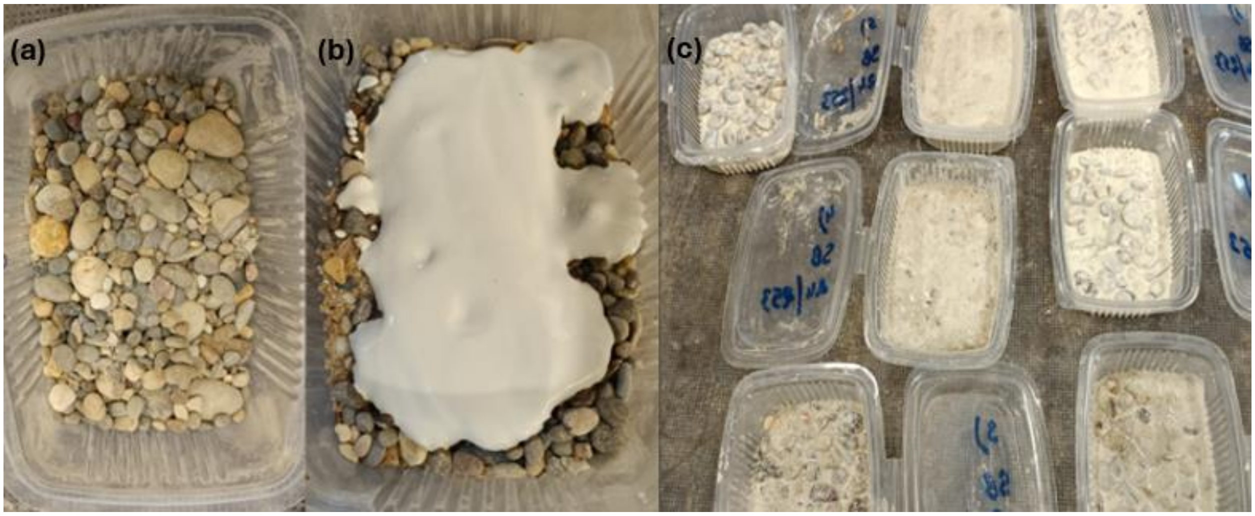

Figure 3Steps to prepare samples for surface texture influence: (a) Prepare concrete samples with varying aggregate sizes. (b) Pouring the binder mixture over the aggregates. (c) Compaction of the samples using vibration.

Table 2: Composition of samples for surface roughness influence

Samples (kg)	Coarse Aggregate (8-20 mm)	Medium Aggregate (2-8 mm)	Sand (0-4 mm)	Binder
1	0.273	0.1	-	0.2
1B	0.273	0.1	-	0.15
2	0.273	-	0.1	0.1
3	0.273	0.1	0.1	0.1
4	-	0.23	0.23	0.15
5	-	-	0.47	0.30
6	0.47			0.15

pH Influence on Germination: Solutions with different pH levels were used to create substrates with varying alkalinity and evaluate the effect on seed germination and growth. Table 3 Shows the concentrations of either calcium hydroxide ($Ca(OH)_2$), sodium hydroxide ($NaOH$), or potassium hydroxide (KOH) needed to obtain pH levels of 8, 9, 11, or 13. Demineralized water was used to obtain a pH of 7. These solutions were added to sand-filled containers mimicking dune environments.

Table 3: Preparing solutions for pH influence test

Mg/l	**KOH**	**NaOH**	**$Ca(OH)_2$**
pH 8	0,056	0,04	0,037
pH 9	0,56	0,4	0,37
pH 11	56	40	37
pH 13	5610	4000	3700

These hydroxides were selected because calcium hydroxide ($Ca(OH)_2$) is a common component in Portland cement and blended cement (with low pozzolanic additions). In contrast, sodium hydroxide ($NaOH$) and potassium hydroxide (KOH) are more soluble and less commonly used in conventional cement. However, they may be present in alkali-activated mixes, which were not explored in this study. Sodium (Na^+) is also one of the primary ions in seawater, making these hydroxides relevant for simulating marine environments.

Experimental Setup: The solutions were applied to sand-filled containers with 18.5 x 13.5 x 6.5 cm^3 dimensions to mimic natural dune environments. As illustrated in Figure 4, each container was filled with two layers of sand (350 g per layer, 0-4 mm grain size). The first layer was saturated with the prepared solutions to prevent seed desiccation while avoiding drowning. Ten marram grass seeds were evenly spaced on the sand surface of each container and covered with an additional 1-2 mm layer of sand.

The containers were maintained under controlled day/night cycles with light from 5 a.m. to 8 p.m. at temperatures between 19 °C and 21 °C. To maintain consistent moisture levels, the containers were covered with plastic film. Each sample had a twin for replication, and this experiment was repeated three times.

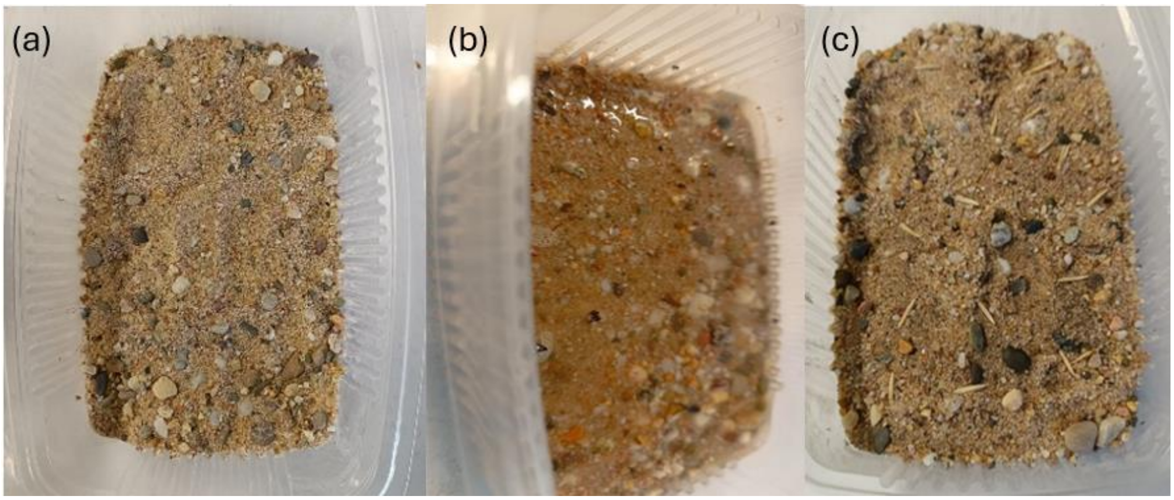

Figure 4: The steps for preparing samples for pH tolerance of marram grass are (a) first layer, (b) saturation of the first layer, (c) another layer of sand with the seeds

2.3.4 Number of Replicates & Statistics

For statistical reliability, each test involved multiple replicates. The seed germination tests, for example, had three replicates and were conducted three times, and the mechanical tests followed standardized practices with three values. The test for pH influence on germination was repeated three times, with each sample having a twin, and the same principle was used for surface roughness influence. Germination probabilities were tested using logistic regression, with testing period (three temporal blocks), and either substrate, pH/solution and roughness as dependent variables. We report overall test statistics compared to an intercept-only null model and, in case of statistical significance (two-sided tests, $p<0{,}05$), the specific contrasts. We also report the mean height of the plants after 20 days of development, analyzed by Gaussian regression analyses (ANOVA). All analyses were done using the glm and emmeans packages (Lenth, 2017), (*R Core Team*, 2023) in R 4.3.

2.3.5 Controlled Environmental Conditions

Temperature and Moisture Control: The environment was kept at 19-21°C for biological tests, with a controlled day/night cycle from 5 a.m. to 8 p.m. to simulate daylight conditions. Plastic coverings retained moisture, ensuring consistent conditions throughout the experiment. These controlled conditions are optimized for reproducibility, providing valuable insights into material performance. However, it is worth noting that they do not fully represent real-world coastal environments, which are more variable and dynamic. Therefore, these tests serve primarily as an optimization step rather than a direct representation of field conditions.

3. Results and discussion

The results of task 15.1 highlight the potential of bioreceptive cement formulations to balance mechanical performance with ecological functionality. Comprehensive testing revealed key findings regarding the chemical, physical, and biological properties of the tested materials.

3.1 Performance of cement formulations

3.1.1 pH evolution

Figure 5 shows the pH of the different mortar mixes from Table 1. The mix with 30% BA resulted in the lowest pH; an unexpected pH rise for the 50% BA mix was observed. This deviation may be attributed to chemical interactions at higher BA concentrations, potentially introducing alkaline compounds into the mix. However, the higher pH values observed will likely decrease over time due to carbonation upon environmental exposure. The observed variation in pH highlights the possibility of testing the pH variation's influence on bioreceptivity.

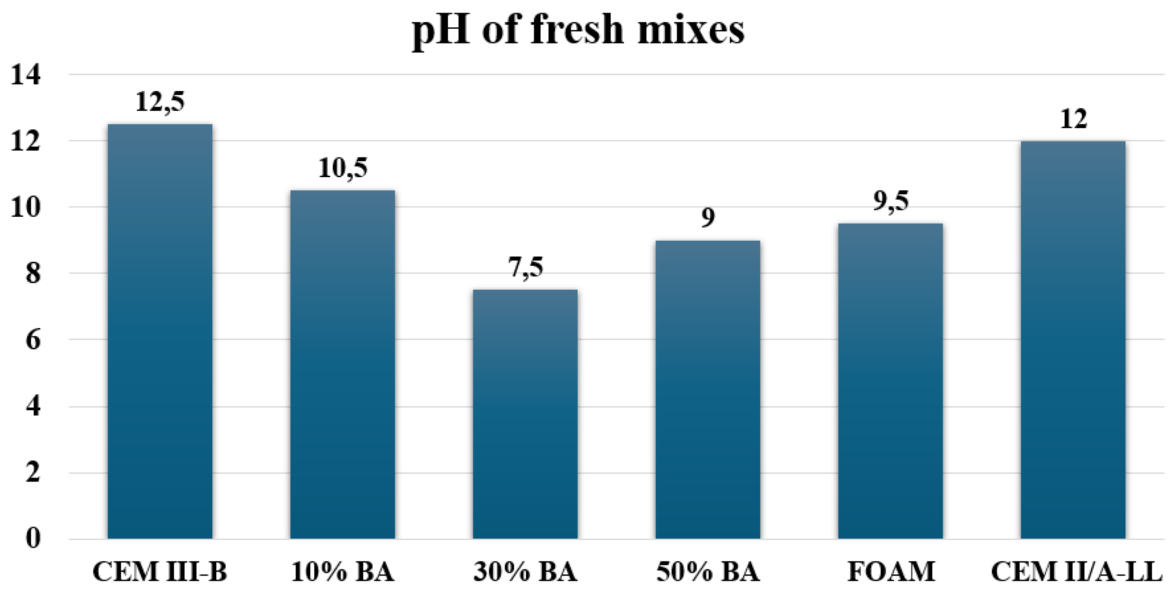

Figure 5: pH of fresh mixes.

3.1.2 Mechanical properties

The graphs show that bending strength is maintained or slightly improved with bone ash (BA) substitutions up to 30%, with values comparable to the reference mix (REF). Compressive strength is reduced with the addition of BA. However, at 50% BA, both strengths drop significantly, indicating reduced structural integrity which may mean these mixes will be suitable only for non-structural applications (see Figure 6).

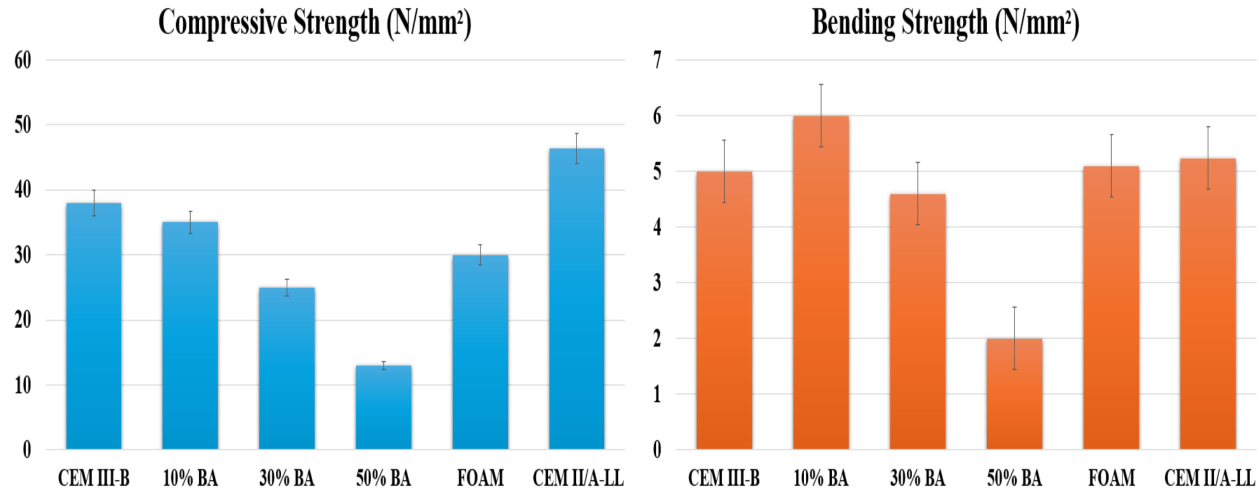

Figure 6: Strength results after 28 days of curing; error bars indicate standard deviation.

Compression testing confirmed significant differences in mechanical strength across all tested substrates. Statistical analysis revealed a highly significant effect of substrate on compressive strength (Chi^2 = 3047.5; $p < 0.001$), with all pairwise comparisons also yielding significant differences (all $p < 0.001$). This indicates that each substrate formulation leads to a distinct compressive strength profile, underlining the importance of substrate choice in structural performance.

In terms of bending strength, the 50% Bone Ash (BA) formulation performed significantly worse than all other mixes. The effect of substrate on bending strength was significant (Chi^2 = 26.03; $p < 0.001$), and post hoc pairwise comparisons confirmed that the 50% BA mix had significantly lower bending strength than all others ($p < 0.001$ for all comparisons involving 50% BA). No significant differences were observed among the remaining substrates for bending strength, suggesting that lower levels of bone ash substitution (≤30%) and other binder types preserved flexural integrity.

3.1.3 Biological Growth Performance

The results highlight that the conducted experiments provide insight into the biological growth performance of cementitious mixes, focusing on their ability to support ecological functions.

Germination tests

The germination tests aimed to evaluate the growth potential of marram grass using the sample mortar prisms after drilling 4 holes (see Figure 1), after 20 days, still no germination was observed. The reasons were considered to be the drying out of the small, drilled holes leaving insufficient moisture for germination. The seeds were not lying flat in the holes (since the holes were relatively small), which may limit their ability to germinate. In addition, it was observed that the MPC sample dried quickly, and the water turned into a hardened gel with sand, blocking seeds from germination, possibly due to the inadequate magnesium-phosphate ratio used for this mix. (Bennouna, 2019).

Figure 7 Shows that the revised setup yielded successful germination for several of the cementitious mixes. The mixes supported moderate growth with plants reaching different heights (see Table 4).

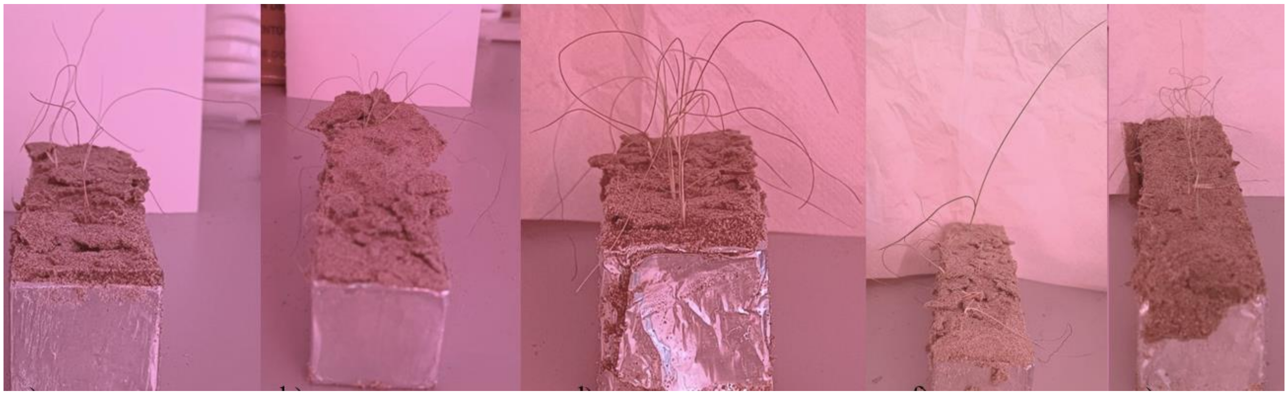

Figure 7: Variation in seedling growth after 20 days of germination

Germination rates differed among the different substrates (Chi^2= 158.34 ; df=9; $p< 2.2e-16$). Pairwise contrasts showed, besides overall absence of germination on MPC, significantly lower germination rates on substrates with concrete mixes (posthoc contrasts; $p<0.05$; for sand-10%BA contrasts $p<0.01$). The size of the shoots differed among successful treatments (Chi^2= 24.94; df=9; $p<0.001$), with the 50% BA mix showing the highest average shoot length (11.60 cm) among the cementitious substrates. Although germination rates for 50% BA were slightly lower than some other mixes, the resulting seedlings exhibited superior growth in terms of height.

The MPC mix, however, did not support germination, likely due to water interaction with magnesium phosphate.

Table 4: The number of germinated seeds per replicate (on a total of 6 seeds present) and the average growth height after 20 days of germination

	Nb of germinated seed									Germination probability	Average Height (cm)
	1st replicate 26- December			2nd replicate 8-January			3rd replicate 5-February				
CEM III-B	3	6	5	6	5	5	3	6	5	81	9.74
CEM II/A-LL	4	4	5	5	4	4	4	4	3	69	7.44
10% BA	4	4	6	6	5	6	4	4	6	83	8.17
30% BA	4	5	4	6	5	6	4	5	4	80	8.53
50% BA	6	4	3	5	5	6	6	4	2	76	11.60
Foam	4	5	5	3	5	5	6	5	5	80	9.07
MPC	0	0	0	0	0	0	0	0	0	0	-
Sand	6	6	6	6	6	6	6	6	6	100	12
Soil with Sand	6	6	6	6	6	6	6	6	6	100	13
Sand/ Plastic	6	6	6	6	6	6	6	6	6	100	11.5

pH tolerance of marram grass

The germination rates of marram grass seeds were monitored daily over two weeks to assess the effect of pH on seed germination and growth. The pH levels of various solutions, including water, KOH, NaOH, and $Ca(OH)_2$, were adjusted to range from pH 7 to 13. Observations focused on both germination success and overall seedling growth. The results of these observations are presented in Figure 8 and Table 5.

Figure 8: Example of the germinating seeds (NaOH-pH9)

Table 5: Effect of pH Levels on Seed Germination and Plant Height in Different Solutions

Solutions	**pH**	**Nb of seeds germinated per 10 seeds present**						**Germination probabilities (%)**	**Average Height (cm)**
		1st replicate 26- December		2nd replicate 27-January		3rd replicate 17- March			
Water	7	3	5	6	6	6	6	53	13,5
KOH	8	2	0	3	3	2	2	20	14,1
	9	2	3	2	3	2	1	16.67	15
	11	5	4	4	3	2	2	30	15
	13	0	1	1	0	1	0	1.7	14

NaOH	8	2	1	3	1	1	2	18.3	17
	9	4	1	4	3	2	3	30	14
	11	4	3	3	1	3	1	18.3	13
	13	1	1	1	1	1	1	10	6,5
$Ca(OH)_2$	8	1	2	2	4	2	1	23.33	13
	9	2	4	3	4	1	1	30	15
	11	2	5	2	4	4	3	28.3	13
	13	3	3	3	3	1	1	16.7	15

Figure 9 shows the germination probabilities across the different pH levels and solutions. This figure suggests water (pH 7) shows the highest germination success, followed by NaOH and $Ca(OH)_2$ solutions at pH 9. Germination probabilities consistently decrease at higher pH values, especially at pH 13. These results are not statistically significant since the species germination varied independently of the pH and solution (pH*solution effect: Chi^2= 2.15; P=0.83; Solution effect Chi^2=1.77; P=0.62; pH effect: Chi^2=0.17; P=0.68). Shoot length, in the contrary, varied by the Solution x pH interaction (Chi^2=33.18; P=0.01), declining with 2.5 cm per unit pH increase in NaOH solutions. On average, the height decline with an increased pH was 0.53 cm per unit pH increase. Interestingly, while germination was highest in water (pH 7), plants grown in water tended to be shorter compared to those in other solutions at similar pH levels.

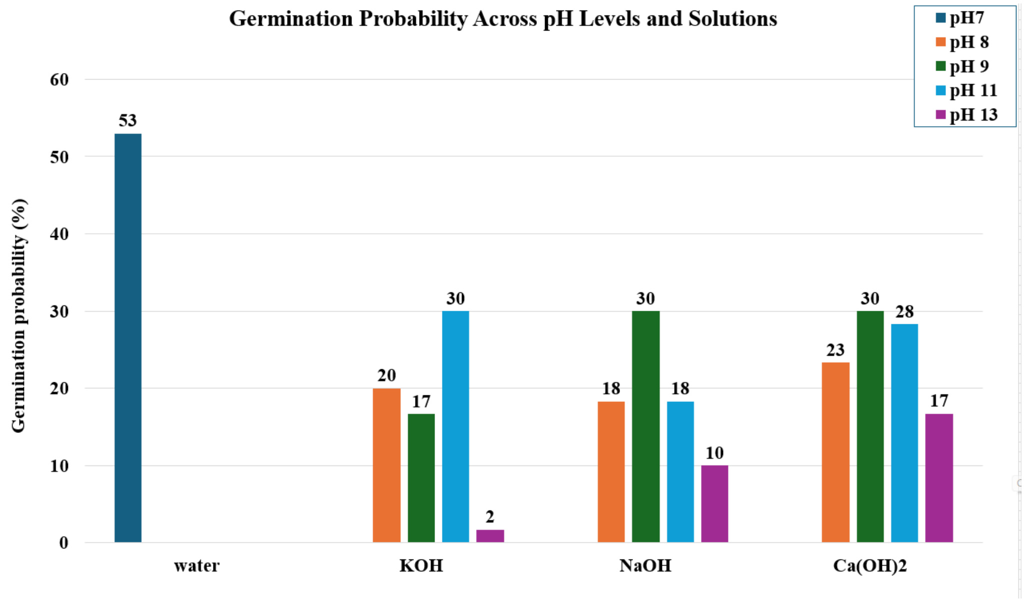

Figure 9: Germination probability across pH levels and solutions

Surface texture influence

The results are presented in Figure 10 and Table 6. Germination rates were not affected by the roughness x carbonation treatment ($Chi^2=1.28$; $P=0.93$), and neither by the roughness treatment – ($Chi^2=1.65$; $P=0.89$). Germination rates, however, nearly doubled with the carbonation treatment ($Chi^2=4.37$; $P=0.04$). Plants were also on average 2.4 cm taller under this treatment ($Chi^2=4.20$; $P=0.04$). Height increases for carbonated samples, although not in the Sample 2 (interaction effect substrate * carbonation: $Chi^2=117.86$; $P<0.01$).

While rougher surfaces supported seed adhesion and moisture retention, these trends were not statistically significant. Still, surface roughness may play a supportive role in seed stability, especially when combined with carbonation.

For carbonated samples, germination was notably higher compared to non-carbonated samples. This suggests that reducing the pH of the surface enhances biological growth, likely by making the material more bioreceptive. Carbonated surfaces provided an optimal environment for seed adhesion and growth, emphasizing the combined importance of surface texture and pH reduction in promoting successful plant development on bioreceptive concrete.

Figure 10: Germinated seeds on a carbonated sample after 2 weeks

Table 6: Results for the surface texture influence on germination (number of seeds germinated of a total of 10) and growth height for the carbonated and non-carbonated samples

Samples	Qualitative roughness	Non-Carbonated samples			Height (cm)	Carbonated samples			Height (cm)
		Nb of seeds germinated				Nb of seeds germinated			
1	4	0	0	1	7	2	1	1	12
1B	4	1	2	0	9.5	2	2	1	10.5
2	3	2	1	1	11	4	2	2	13
3	4	0	0	0	0	3	1	1	8.5
4	5	0	0	1	8	3	3	2	11
5	6	0	0	0	0	3	3	1	11
6	7	2	1	1	9.5	4	2	3	10

The results presented in the Table 6 are derived from three test replicates, recording the number of germinated seeds and their respective growth heights (cm) over two weeks for both carbonated and non-carbonated samples.

Surface roughness was rated on a scale from 1 to 7, with 1 being the smoothest and 7 the roughest. Coarse aggregates (8-20 mm) created rougher surfaces, while finer aggregates or more sand led to smoother surfaces. Though not statistically significant, rougher surfaces tended to improve seed stability and moisture retention.

Overall, carbonated surfaces showed the most consistent improvement in germination and shoot height. Combining carbonation with textural variation may offer ecological benefits, but carbonation was the primary driver of improved bioreceptivity.

4. Conclusion

The findings of this report demonstrate that bioreceptive cement formulations hold substantial potential for promoting biological growth and contributing to the development of sustainable coastal defenses. Among the materials tested, Bone Ash mixes (up to 30%), Foamed Concrete, and CEM II/A-LL exhibited promising bioreceptive properties while maintaining acceptable mechanical strength. However, higher bone ash content (50%) significantly reduced compressive and bending strength, limiting its structural suitability.

Carbonation emerged as a key factor in enhancing biological performance. It significantly improved germination rates and shoot height across multiple substrates, confirming that surface pH reduction is an effective strategy for increasing cement bioreceptivity. In contrast, surface roughness appeared to support seed adhesion and moisture retention, but these effects were not statistically significant. However, the interaction of rough surfaces with carbonation may still provide ecological benefits and warrants further exploration.

Despite its low pH, magnesium phosphate cement (MPC) did not support seed germination under the tested conditions, likely due to chemical incompatibilities (Magnesium to phosphate ratio) and unfavorable water retention properties.

From a biological perspective, marram grass showed good germination and growth on sand-based controls and several low-pH cementitious substrates. Substrate type strongly affected germination probability, and plant height was significantly influenced by material composition and chemical conditions such as pH.

Altogether, these results underscore the importance of optimizing chemical (e.g., carbonation, binder composition) and physical (e.g., porosity, surface texture) characteristics in developing eco-engineered building materials. Future work should focus on scaling these findings through field trials, integrating 3D printing technologies, and refining substrate mixtures for complex eco-dike geometries.

5. References

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