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Application of various binders in soil stabilisation for road batter protection

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Abstract. The study investigates the use of various binders for soil stabilization to enhance road batter protection under extreme hydraulic conditions. Flash floods and high-velocity water flows in rural areas often lead to significant erosion, posing challenges for infrastructure sustainability. This research aimed to identify cost-effective and efficient binder combinations suitable for protecting soil surfaces against severe erosion. Disturbed soil samples were mixed with agricultural lime, gypsum, and triple blends at varying proportions and subjected to controlled weathering and flume tests at velocities of up to 2 m/s. The results revealed that triple blends, at proportions of 2 % and 3 %, demonstrated the most effective erosion resistance, with unconfined compressive strengths exceeding 1 MPa. In contrast, gypsum showed limited efficacy due to uneven binding distribution. The study concludes that optimal binder selection and application can significantly reduce erosion susceptibility, offering a sustainable solution for rural infrastructure protection.

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1. Introduction

Soil erosion is a common problem for transportation infrastructure projects, mainly road embankment slopes, causing significant damage due to flash floods. Strong water flow can lead to erosion, damaging the embankment and underlying soil layers and resulting in road surface cracks and subsidence [1]. While using concrete for slope protection is effective, it is costly, especially for traffic projects in rural areas with low traffic density and limited budgets. Therefore, finding cost-effective alternative solutions is essential. This study uses binders to stabilize the soil and protect the road embankment, contributing to enhanced sustainability and safety for the transportation system.

The traditional binders used in soil stabilization include Portland cement, lime, and fly ash, which have been extensively studied for their effectiveness in enhancing soil strength and stiffness. For instance, Tsai et al. highlighted that adding fiber-mixed binders can significantly improve the compaction and California Bearing Ratio (CBR) characteristics of sandy clay, demonstrating the potential of composite binders in soil stabilization [2]. Similarly, Lindh and Lemenkova emphasized that different soil types require specific stabilizers; coarse-grained soils benefit from Portland cement and fly ash, while fine-grained soils are more effectively stabilized with lime or a combination of lime and cement [3]. This distinction is crucial for engineers when selecting appropriate binders for specific soil types. In addition to traditional binders, alternative materials have gained attention due to their environmental benefits and effectiveness. For example, Du et al. explored using a phosphate-based binder for stabilizing soils contaminated with heavy metals, demonstrating that such binders can reduce leaching and enhance soil strength [4]. This approach aligns with the growing trend of using waste materials and by-products in soil stabilization, improving soil properties, and addressing environmental concerns related to waste disposal [5]. Integrating alternative binders, such as ground granulated blast furnace slag (GGBS) and fly ash, has enhanced the mechanical properties of stabilized soils while reducing the carbon footprint associated with traditional cement production [6]. Their dosage and the water-binder ratio also influence the effectiveness of binders in soil stabilization. Lindh's research indicated that the water-binder ratio significantly affects stabilized soils' strength and seismic behavior, suggesting that careful control of this parameter is essential for achieving desired stabilization outcomes [7]. Moreover, Pham et al. found that increasing the binder leads to higher unconfined compressive strength (UCS) and reduced permeability in stabilized clayey soils, underscoring the importance of optimizing binder content for effective stabilization [8]. This optimization process is critical, as excessive binder use can lead to economic inefficiencies and environmental impacts. The application methods for binders also vary, with techniques such as deep soil mixing (DSM) and dry soil mixing commonly employed. Timoney et al. described the dry soil mixing method, where binders are injected in powder form into the soil, effectively enhancing the geotechnical properties of organic soils [9]. This method is particularly advantageous in areas with high moisture content, as it minimizes water-related issues during stabilization. Additionally, biopolymer binders, such as xanthan gum, have emerged as a promising alternative, offering unique properties such as high viscosity and hydrophilicity, which can improve soil stability and reduce erosion [10, 11]. The interaction between binders and soil also plays a significant role in determining the effectiveness of stabilization. The chemical reactions that occur during the hydration of binders, particularly with calcium silicate and alumina, contribute to the increased strength and durability of the stabilized soil [12]. Furthermore, using admixtures, such as sodium chloride as a cement accelerator, has enhanced the early strength gain of stabilized peat, indicating that the choice of binder and its additives can significantly influence stabilization outcomes [13]. Environmental considerations are increasingly influencing the selection of binders for soil stabilization. Alkali-activated binders and geopolymers have been explored as a sustainable alternative to traditional cement, offering similar or improved performance while reducing environmental impacts [14, 15]. The decision-making model proposed by Rocha et al. emphasizes the importance of minimizing costs and environmental impacts when selecting binders for soil stabilization, reflecting a broader trend toward sustainable engineering practices [16–18].

Although extensive research has been done on using binders for soil stabilization, studies focusing on protecting road embankment slopes, particularly in rural areas, are still lacking. Moreover, selecting the appropriate binder must be based on the specific factors of each project, including soil type, climatic conditions, technical requirements, and budget [19, 20]. This study is conducted within a confidential project in Queensland, where cost-effective and efficient solutions are sought to protect embankment slopes from erosion. The results of the survey will provide valuable information for selecting and applying binders in slope protection, contributing to the effectiveness and sustainability of the project.

2. Materials and Methods

2.1. Soil Preparation

So as to investigate the effect of binders, soil must be tested under controllable conditions in the laboratory. The Department of Transport and Main Road (DTMR) sampled the soil. Then, it was mixed with various binders at the DTMR laboratory. Four binders were selected based on commercial availability: agricultural lime, gypsum, triple blend, and emulsion (residual bitumen). However, the emulsion was eliminated due to environmental concerns. The triple blend comprises 30 % general-purpose cement, 30 % fly ash, and 40 % hydrated lime.

The main effect of binder is to build a C-S-H binding force, which comes from Calcium, Silicon, and Hydrogen. The binders contribute Calcium (Table 1), while the soil has over 50 % mass of SiO_2. Hydrogen is available in the soil's moisture content.

Table 1. Calcium component in binders.

Binder	Calcium (% mass)
Agricultural lime	37–40 %
Gypsum	27–31 %
Triple blend	35–46 %

A previous study on lime showed that 3.25 % of lime could significantly prevent erosion at a ratio of 3.75 %, and erosion is negligible at a ratio of 5.25 % of lime [20]. Due to economic constraints, the binders were mixed at lower different ratios. Agricultural lime and gypsum were mixed at 0.5 %, 1.5 %, and 2.5 % of mass. Meanwhile, the triple blend was mixed at 1 %, 2 %, and 3 %, thanks to its availability.

After that, the mixtures were molded in acrylic boxes with a plastic tamper and 3D printed to the appropriate size (Fig. 1). A compaction by layer may be required to reach the desired relative density of 97 %. The box's width was selected after the maximum power of the pump so that it could supply water at the velocity of 2 m/s over the sample in the flume test. The length and the depth were deterred from a previous erosion study so that the soil sample was thick enough for the developed erosion [20].

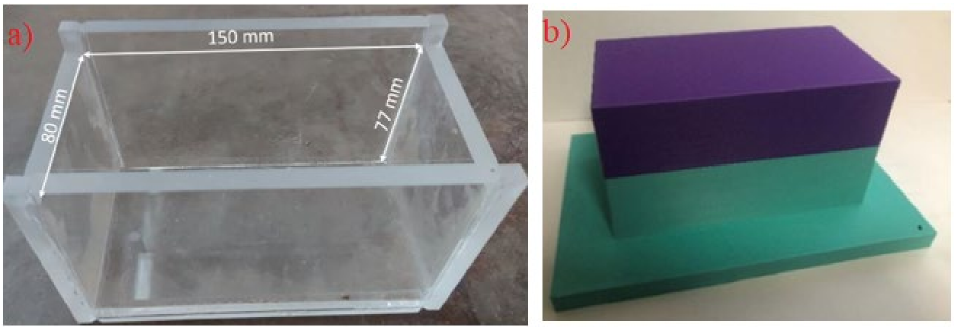


Figure 1. Sample mold: (a) acrylic box and (b) plastic tamper.

Before testing, samples were exposed to the weather for 5 weeks (Fig. 2). This sun bath simulates the weather effect on the ground surface. As a result, the top surface was dried and more susceptible to erosion. Ambient temperature varied from 22 °C to 38 °C, and humidity varied widely from 20 % to 80 %. However, no significant surface crack was observed.

Figure 2. Samples in sun exposure.

2.2. Laboratory Testing

Flume test. After the preparation, samples were tested with strong overflow of 0.5, 1.0, and 2.0 m/s. DTMR required the velocity for various probabilities of flood [21, 22]. These velocities already accounted for a heavy safety factor since actual flow may have a higher thickness, which results in a lower velocity at the flow bed. TUFLOW and ANSYS simulation can derive a detailed estimation [23 - 25].

The surface erosion apparatus was 3D printed in 5 pieces and assembled with a seal (Fig. 3). To reduce turbulence, the apparatus employed a laminator at the upstream side. The downstream side is empty to minimize backflow due to clogging.

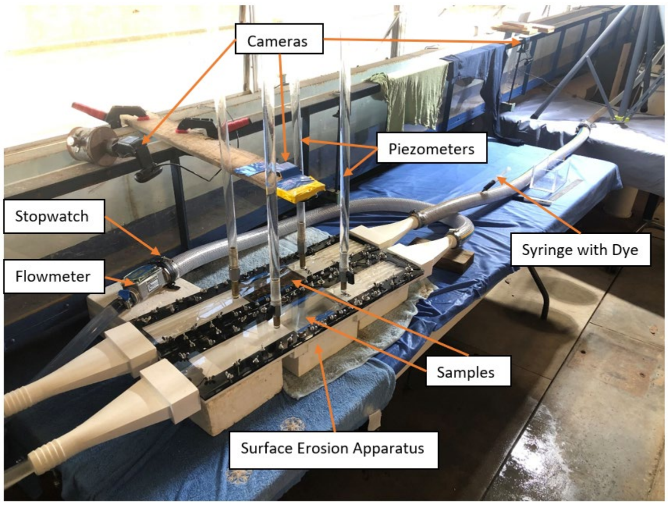


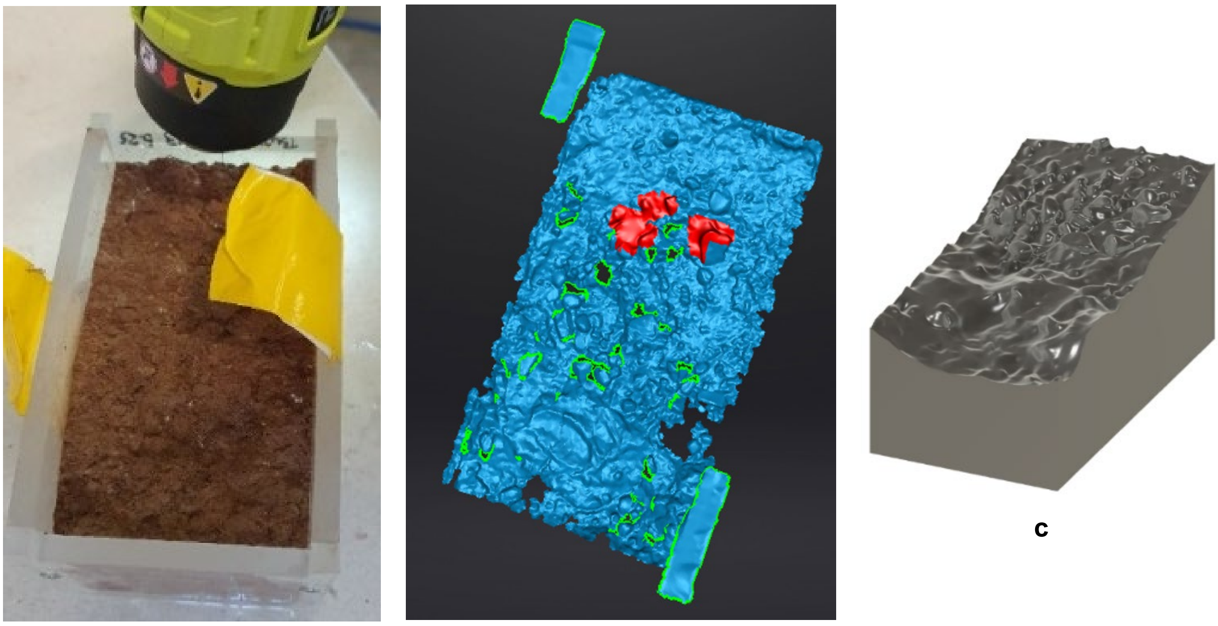
Figure 1. Flume test setup.

However, a trial showed that monitored water pressures still changed very quickly. Sometimes, the value at the upstream side is lower than at the downstream. Although there was a recommendation to use more sensitive sensors [9]. The sensing rate of the employed Wika A-10 and the recording rate of the DT85 data logger were already milliseconds. Hence, a decision was made to go in the opposite direction. 3 m piezometers were attached to reduce the fluctuation. The water heads still fluctuated but at a very slow rate, and the pressure at the upstream side was consistently more significant than the pressure at the downstream.

Four high-resolution webcams controlled by authorial software monitored the flume test. These cameras monitored a flow meter, a timer, samples, and the piezometers. The test on each sample was run continuously for 24 hours.

Data processing. After testing, samples were dried with a heat gun until no water was visible at the surface (Fig. 4a). Then, the surface was obtained with an EinScan Surface Light scanner. This portable scanner could help scan tricky corners. However, there were still several mesh failures, which must be patched (Fig. 4b). The surface data was transformed into a com-putable mesh with Shining 3D and Fusion 360 (Fig. 4c). After that, the eroded volume and erosion depth were computed. The average eroded depth, D, is calculated as D = Volume loss/Sample Area.

However, the actual depth may vary by location. Hence, erosion depth at various distances from the edge of the sample was also measured.



a b c

Figure 4. Surface scan: (a) sample drying after the test, (b) scanned topography, and (c) remaining volume.

3. Results and Discussion

A summary of test results is presented in Table 2. Gypsum has no effect on erosion protection with the given mass proportions. In contrast, it increased the eroded volume to the maximum. This may be caused by the fact that gypsum provided some binding force, but it was not distributed well due to the low mass proportions. Hence, some agglomerates were formed. However, there was not enough binding force globally. These agglomerates suffered more drag force and were more susceptible to erosion. This explanation may also be proper for the sample with a low proportion of agricultural lime and triple blend. Binders had a negative effect when a low proportion of binder could form ag-glomerates but could not bind the whole soil mass.

Table 2. Eroded volume (cm^3).

V (m/s)	No binder	Agricultural lime			Gypsum			Triple blend		
		0.5 %	1.5 %	2.5 %	0.5 %	1.5 %	2.5 %	1 %	2 %	3 %
0.5	89.70	122.6	131.3	136.7	180.3	210.1	197.0	232.2	17.9	18.6
1.0	230.64	254.7	221.1	230.4	406.2	420.0	398.8	502.5	37.6	51.6
2.0	620.40	676.8	924.0	357.6	924.0	924.0	924.0	671.6	53.8	39.3

Agricultural lime showed some effect of treatment. However, the efficacy of the tested proportions was not yet satisfactory. The test of the sample with 1.5 % lime and 2.0 m/s flow was an interesting case when some gravels enhanced the erosion. Meanwhile, the triple blend showed good efficacy at proportions of 2 % and 3 % by mass.

Notably, the eroded volume may differ from the computed value due to the erosion (Fig. 5). After a significant erosion, the sample surface might not be exposed to strong flow anymore. Hence, it would have less shear stress. However, the turbulence might increase the direct impact on the surface. As a sequence, the everyday stress would increase. A previous study proposed to extrude the sample 1 mm into the flow to keep the flat surface [25]. This might not entirely reflect the surface erosion because the top layer might be peeled off by everyday stress from the intense flow rather than the shear stress. In addition, it may also cause some destruction at the boundary due to the sample extrusion. To illustrate the impact, the profile of eroded surfaces was built from 4 key points, the midpoints of sample quadrants (Fig. 6).

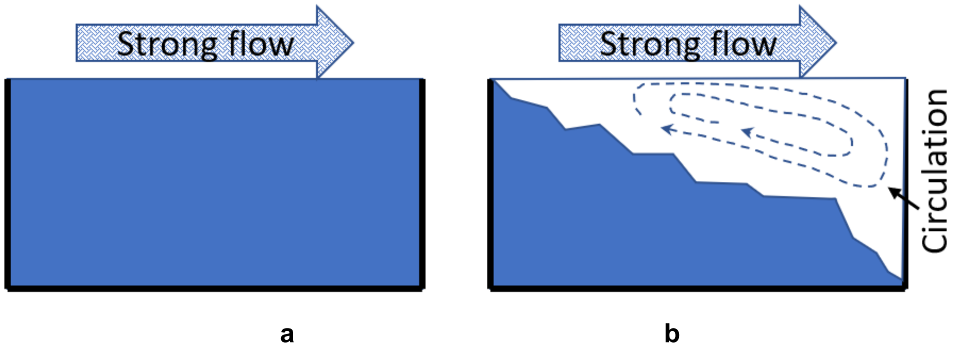


Figure 5. Flow pattern on tested specimen: (a) before the erosion and (b) after the erosion.

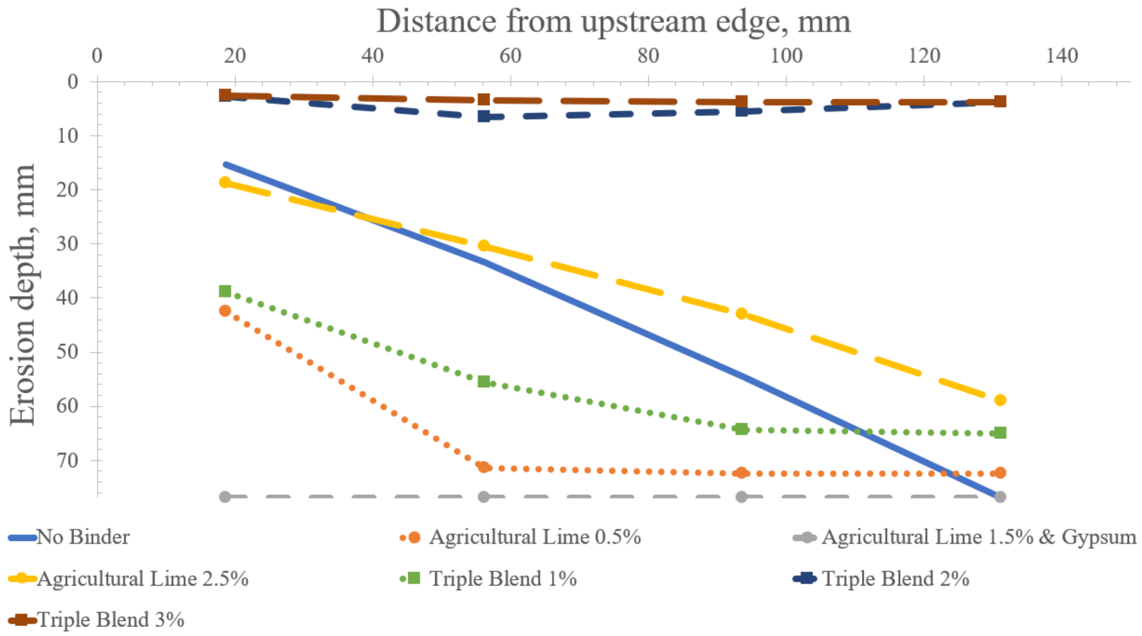


Figure 6. Surface profiles after tests with the 2 m/s flow.

The graph shows that samples with 0.5 % agricultural lime and 1 % triple blend suffered damage from everyday stress rather than shear stress. Hence, the surface was not straight but leveled off after a distance.

In contrast, samples with 2 % and 3 % of triple blends showed adequate protection. Indeed, the strong over-flow peeled off only the weathered top layer. These samples were damaged by shear stress rather than everyday stress. UCS tests were undertaken to see how strong the samples were bound. The direct link between erosion protection and UCS seemed obvious (Fig. 7). Although the strength requirement depends on the flow velocity of the flood, samples with a 3 % triple blend had UCS over 1 MPa, which stepped into the zone of very weak rock.

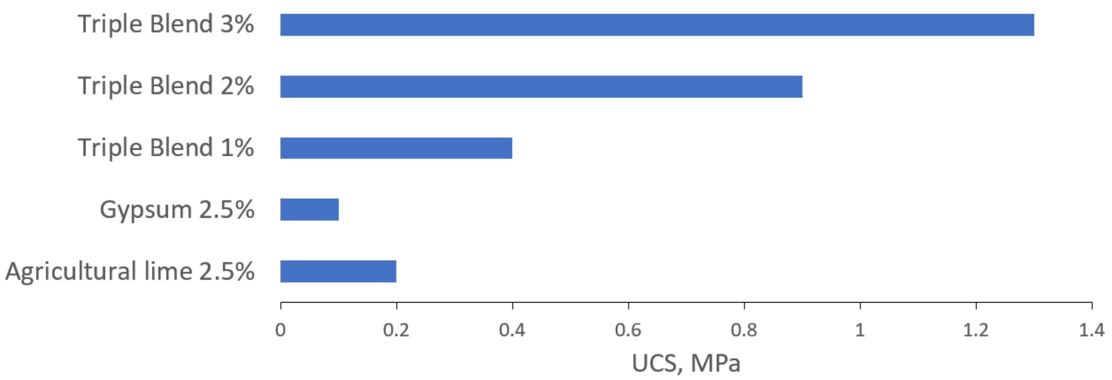


Figure 7. Unconfined compressive strength of samples with binders.

4. Conclusion

The paper presents a study on the impact of various binders on soil erosion susceptibility. Some striking discoveries have been concluded:

- If the proportion of the binder is not high enough, the binder may negatively impact erosion protection due to the formation of agglomeration.
- Samples with 2 % and 3 % of triple blends seem to have adequate protection as only the weathered top layer was eroded. Note that this layer was dried during the curing process.
- UCS of roughly 1 MPa can be a good sign for an effective binder.

Future studies may focus on the impact of everyday stress during the erosion.

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