Organo-Mineral Complexes for Water Purification: Experimental and Statistical Analysis

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Abstract: The article presents an assessment of the sanitary and hygienic condition of water in storage ponds at solid waste landfill facilities, with the aim of enabling their reconstruction, expansion, and reclamation of bottom sediments. Based on experimental and statistical modelling, the optimal composition of an organo-mineral complex for the removal of suspended solids from technically contaminated water was determined. Water transparency with turbidity below 1 Nephelometric Turbidity Unit is achieved using 2.2 to 4.2 % quicklime, 7.5 to 11.25 % bentonite, and 6 to 10 % enzyme. The optimal composition of the organo-mineral complex for sediment formation was also established. The resulting precipitate exhibits plastic strength up to 160 kPa after 28 days of exposure, achieved with 30 to 35 % quicklime, 0 to 2.5 % bentonite, and 0 to 1.5 % enzyme. The formed sediment is self-sealing and water-resistant, making it suitable for constructing embankments around storage ponds at solid waste landfills to increase both industrial water capacity and evaporation area.

1 INTRODUCTION

Storage ponds at municipal solid waste landfill facilities accumulate technically polluted water whose turbidity and chemical load complicate both reclamation and any subsequent expansion of pond capacity [1]. The water column typically holds an emulsified mixture of petroleum hydrocarbons, fine mineral particles, colloidal organics, and microbial biomass that resists gravity settling alone. Producing a clarified effluent while also generating a consolidated, load-bearing precipitate from a single treatment step would substantially streamline landfill pond management - a goal that motivates the present study [12]. If the treated precipitate can be engineered to meet geotechnical performance criteria, it may serve directly as fill material for pond embankments, turning a waste stream into a construction resource.

2 LITERARY REVIEW AND PROBLEM STATEMENT

Suspended sediment monitoring reported in [2] and [3] show that peak single-event turbidity in drainage systems can exceed 460 nephelometric turbidity units (NTU). Passive retention structures reduce the downstream transport of suspended solids but cannot alone deliver effluent clarity suitable for reuse or discharge without additional treatment.

Plant-derived coagulants - cactus-pad mucilage and watermelon-seed extract - were assessed for pond-water clarification in [4], achieving turbidity removal between 78.58% and 94.18%; however, the required settling times were considerably longer than those typical of mineral-based coagulants, limiting their practical throughput.

A hybrid clarifier integrating rotating biological discs into a horizontal settling chamber was engineered and piloted for lightly polluted source water in [5]; the device removed turbidity, dissolved organics, and NH^{+4}-N simultaneously over a 2-hour hydraulic retention time, with effluent quality held stable for over two months; removal reached 73.65 ± 5.15% for turbidity, 53.98 ± 5.17% for TOC, and 77.01 ± 10.02% for NH^{+4}-N leaving residuals of 1.96 NTU, 1.98 mg/L TOC, and 0.46 mg/L NH^{+4}-N in the treated effluent.

Injection of polyacrylamide into turbid pumped water was trialled in [6] using two charge types. Cationic PAM consistently outperformed the non-ionic variant: turbidity in the receiving basin fell by 98% and 90%, respectively, with charge-driven destabilisation identified as the key mechanism responsible for the superior performance of the cationic grade.

A three-stage coagulation–sedimentation–filtration sequence was field-tested on a seasonally turbid urban river in [7]. Applying 50 ppm polyaluminium chloride together with 1.5 ppm PAM, the process removed 99.53% of turbidity and 94.69% of total phosphorus, with the clarified effluent consistently reaching turbidity of < 1 NTU and a TP concentration of up to 0.017 mg/L, which fully complies with Class II for EQSSW.

Electrocoagulation with paired iron–aluminium electrodes was evaluated for aquaculture pond effluent in [8], with a Box–Behnken response-surface design used to map the joint effects of electrolysis time, settling duration, and current density. The optimised parameter set (11.97 min electrolysis, 29.99 min settling, 2.389 A) yielded 91.67% turbidity removal in measured trials, deviating by less than 0.2% from the quadratic model prediction of 91.84%.

Coagulation and flocculation of travertine quarry wastewater were systematically compared in [9] across a pH range of 6–9. Single-stage coagulation proved insufficient regardless of the reagent used, whereas the two-stage coagulation–flocculation sequence restored transparency effectively. Among three coagulants tested, aluminium chloride showed the best pH-6 and pH-9 performance, while differences between reagents largely disappeared at neutral pH. The dominant removal pathway shifted from charge-neutralisation in acidic conditions to sweep coagulation near neutrality, with bridging flocculation governing the polymer-aided stage.

Dubyniak et al. [10] developed predictive models for clarifier operation that couple tank geometry, flow rate, and sediment rheology to measurable output indicators: effluent turbidity, suspended-solids concentration, and particle settling velocity. The models allow reagent dosing and temperature regimes to be adjusted in advance of performance drift, supporting consistent long-term clarification without reactive intervention.

Laboratory compaction and shear-strength tests on silt treated with hydraulic binders (0–8% lime, cement, or both) are presented in [11]. After curing under conditions that included freeze–thaw cycling, all treated specimens exhibited higher internal friction angles and cohesion values relative to untreated controls, with the degree of gain depending on the binder combination and the soil's grain-size distribution. These results underline the potential of lime-rich mineral precipitates - such as those produced by the organo-mineral complex studied here - as a structural fill for embankment construction.

The reviewed literature confirms that no single treatment mechanism is universally adequate: chemical coagulation, biological treatment, and electrochemical methods each address a subset of the pollutants present in landfill pond water, and their performance is highly reagent- and condition-specific. Integrated approaches combining mineral coagulants with sorbents and enzyme preparations offer a route to simultaneous turbidity removal and sediment consolidation, consistent with the resource-efficiency principles articulated in recent environmental-engineering studies [12], [13]. The present work extends our earlier investigation of the lime–zeolite–ECO-NOVA system [14] by substituting bentonite for zeolite and Zeta-Zim for ECO-NOVA, keeping all other experimental conditions identical so that the two sorbent–enzyme combinations can be compared directly. The goal is to identify the compositions that minimise treated-water turbidity and maximise sediment plastic strength, with the end use of building and reinforcing storage-pond embankments at solid waste landfill sites.

3 MATERIALS AND METHODS

3.1 Water Sampling

The studies were conducted using water contaminated by Storage Pond No. 1 on the land plot of the Solid Waste Landfill (SWL) in Chernihiv, Ukraine (the same site as reported in [14]).

The complete physicochemical and radiological characterisation of this water (Measurement Protocols Nos. 1528 and 1528/P dated 15.07.2025, LLC "EKODIYA", Kyiv), including all 24 chemical parameters and radiation indicators, is reported in full in the authors' prior work [14]. The same water source is used in both studies to enable direct comparison of the two organo-mineral systems under identical conditions.

3.2 Selection of Precipitating Reagents

Three components were selected for the organo-mineral complex. Quicklime (CaO) served as the reactive mineral phase; its alkalising action promotes the precipitation of dissolved anions as water-insoluble hydroxide and carbonate salts. Bentonite, a smectite-group clay with a high specific surface area, was incorporated as the adsorbent phase to capture oil-derived compounds, surfactants, and radionuclides via surface sorption. Zeta-Zim (an industrial multi-enzyme preparation) was included to catalyse the hydrolysis and transesterification of fats and petroleum residues, and to cross-link the aluminosilicate layers of bentonite into a cohesive, water-repellent matrix [15]. This combination differs from our earlier formulation [14], which used zeolite and ECO-NOVA enzyme; the present reagent set was selected to evaluate whether a smectite-based system achieves comparable or superior treatment outcomes.

3.3 Experimental and Statistical Modelling

Composition optimisation employed a three-factor simplex-centroid mixture design analysed within the STATISTICA 12 environment. A special cubic model was fitted to account for non-linear binary and ternary interactions among the components. This methodology follows the approach validated in our previous study [14] but is applied here to the novel bentonite–Zeta-Zim system.

The coefficients of variation and the matrix for planning the experiment are given in Tables 1 and 2, and the implementation of the experiment is given in Tables 3 and 4.

Table 1: Variation intervals and values of variable factors.

Factors, type	Natural	Coded	Levels of variation		Variation interval
			0	1	
CaO	%	X1	0	35	17.5
Bentonite	%	X2	0	15	7.5
Zeta-Zim	%	X3	0	10	5

Table 2: Experiment planning matrix.

Plan points	Matrix plan in codes			Full size matrix plan		
	X1	*X2*	*X3*	CaO	B	Z
1	0.00	1.00	0.00	0	15	0
2	0.33	0.33	0.33	11.7	5	3.3
3	1.00	0.00	0.00	35	0	0
4	0.50	0.50	0.00	17.5	7.5	0
5	0.00	0.00	1.00	0	0	10
6	0.50	0.00	0.50	17.5	0	5
7	0.00	0.00	0.50	0	7.5	5

Table 3: Correspondence of coded values to natural values.

Coded	Natural		
	CaO (*X1*)	Bentonite (*X2*)	Zeta-Zim (*X3*)
0	0	0	0
0.25	8.75	3.75	2.5
0.5	17.5	7.5	5
0.75	26.25	11.25	7.5
1.0	35	15	10

Table 4: Summary of experimental results.

Plan points	Turbidity, NTU, after day			Tensile strength, kPa, after day		
	14	21	28	14	21	28
1	519	170	163	0.12	0.8	1.41
2	971	229	169	0.5	0.96	1.94
3	1000	1000	1000	3.77	57.86	160
4	1000	1000	1000	1.18	12.24	57.86
5	8	3.49	1.02	0	0	0
6	772	376	212	0.1	0.7	1.49
7	98	103	74	0.1	0.12	1.94

The initial parameters selected were water turbidity $T \rightarrow min$ and sediment plastic strength $T_s \rightarrow max$, which were determined on days 14, 21 and 28 of the holding periods.

3.4 Experimental Methods

To determine water turbidity, we used a portable TB 1 turbidimeter manufactured by VELP SCIENTIFICA, Italy.

The TB1 portable turbidimeter quickly and accurately measures the turbidity of water samples, with results displayed directly in nephelometric turbidity units (NTU).

To determine the plastic strength of the sediment in kPa, a Rebinder cone plastometer weighing 224 g and with an angle of $\alpha=45°$was used. The dependence of plastic strength on the depth of penetration of the Rebinder cone was approximated by the function $y=14.77x^{-1.97}$.

The sample weight was 200 g, depending on the number of components of the organo-mineral complex presented in Table 2. Water was drained from the samples to determine turbidity, and the sediment was used to determine plastic strength.

4 RESULTS

4.1 Determination of Water Turbidity

Regression analysis of the data in Table 4 yielded the following empirical models describing water turbidity evolution as functions of the organo-mineral complex composition at three ageing intervals:

$$T^{14d}=1000X1+519X2+8X3+962X1X2+1072X1X3-662X2X3+8358X1X2X3 \quad (1)$$

$$T^{21d}=1000X1+170X2+3,49X3+1660X1X2-502,98X1X3+65,02X2X3-8044,53X1X2X3 \quad (2)$$

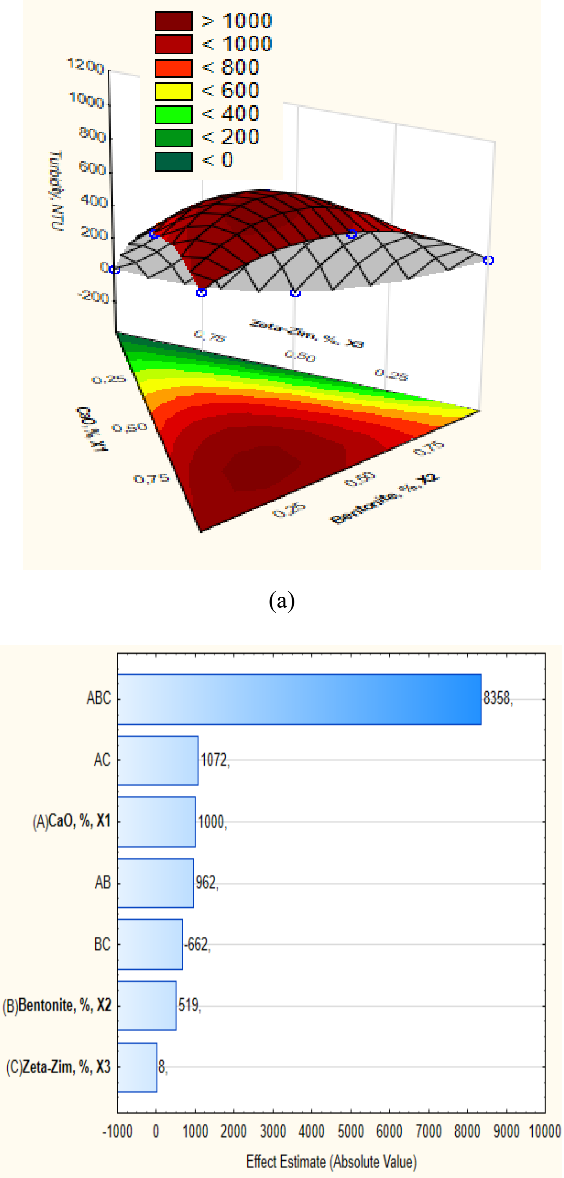
$$T^{28d}=1000X1+163X2+1,02X3+1674X1X2-1154,04X1X3-32,04X2X3-7376,94X1X2X3 \quad (3)$$

Ternary response surfaces (Fig. 1-3) were constructed from the regression equations using the factor designations in Table 2. Compositions at plan points 3 and 4 (Table 4) completely absorbed the water phase; these were assigned a ceiling value of 1000 NTU.

Analysis of regressions (1)–(3) showed that water turbidity after 14, 21, and 28 days of exposure is primarily influenced by the three main factors X1, X2, and X3, which together account for up to 80% of the total effect (see Figures 1b–3b).

As shown in Figure 1a, water turbidity decreases from 519 to 8 NTU after 14 days of exposure when the quicklime content (X1) decreases from 8.75% to 0%, the bentonite content (X2) increases from 14% to 15%, and the enzyme content (X3) increases from 0% to 10%.

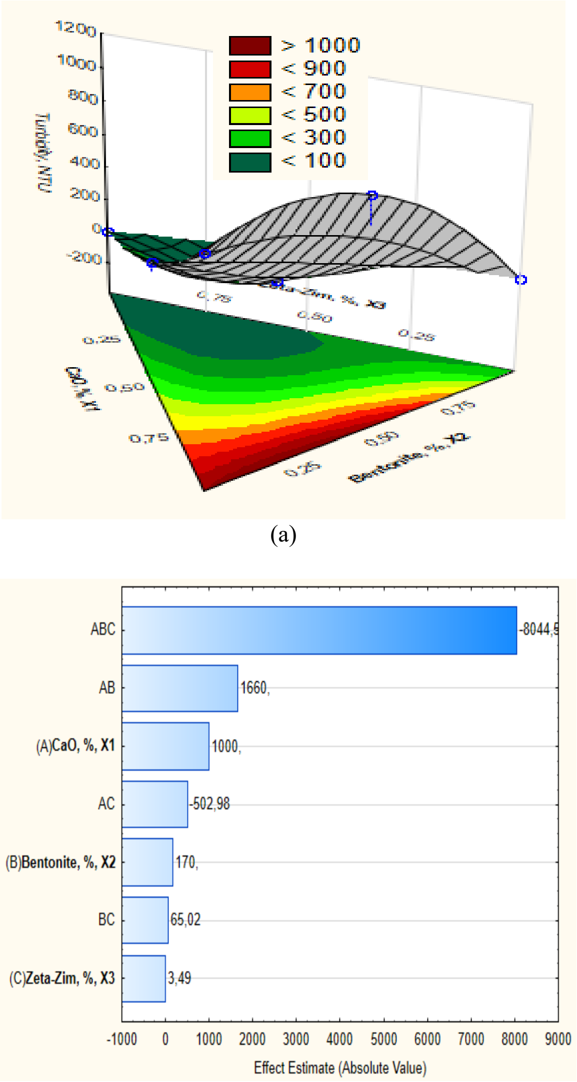
As shown in Figure 2a, turbidity decreases from approximately 400 to 3.5 NTU after 21 days of exposure when the quicklime content (X1) decreases from 17.5% to 0%, the bentonite content (X2) increases from 12.5% to 15%, and the enzyme content (X3) increases from 0% to 10%.



(a)

(b)

Figure 1: Terminal surface: a) and Pareto diagram, b) of water turbidity on the 14th day of exposure to factors of the organo-mineral complex.



(a)

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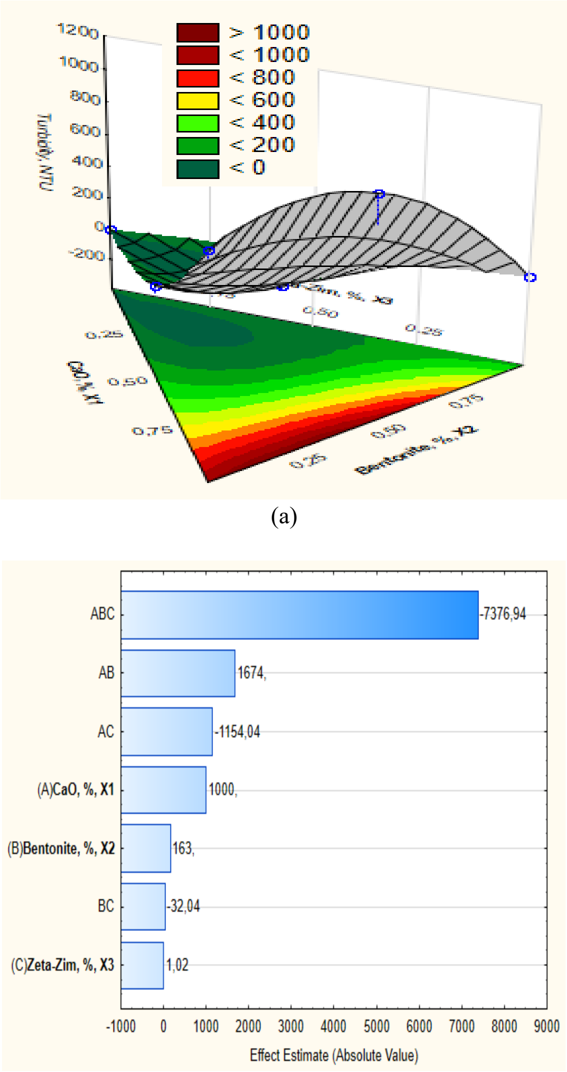
Figure 2: Terminal surface: a) and Pareto diagram, b) of water turbidity on the 21th day of exposure to factors of the organo-mineral complex.

Complete optical transparency (turbidity ≤ 1 NTU) is attained after 28 days of exposure, as shown in Figure 3a. This condition is achieved at quicklime contents ranging from 0 to 17.5% (X1), bentonite contents from 0 to 15% (X2), and enzyme contents from 0 to 10% (X3).



(a)

(b)

Figure 3: Terminal surface: a) and Pareto diagram, b) of water turbidity on the 28th day of exposure to factors of the organo-mineral complex.

Superimposition of the three ternary response surfaces at the transparency threshold ($T \rightarrow 0$), the optimal range of the organo-mineral complex composition was determined. It is defined by quicklime content from 2.2 to 4.2% ($X1$), bentonite from 7.5 to 11.25% ($X2$) and enzyme from 6 to 10% ($X3$). This composition ensures the production of transparent water with turbidity not exceeding 1 NTU.

4.2 Determination of the Plastic Strength of Sediment

Analogous regression modelling was applied to the sediment plastic strength data (Table 4), yielding (4)-(6) for the three ageing periods:

$$Ts^{14d}=3{,}77X1+0{,}12X2+6.7E^{-16}X3-3{,}06X1X2-7{,}14X1X3+0{,}16X2X3+8{,}61X1X2X3 \quad (4)$$

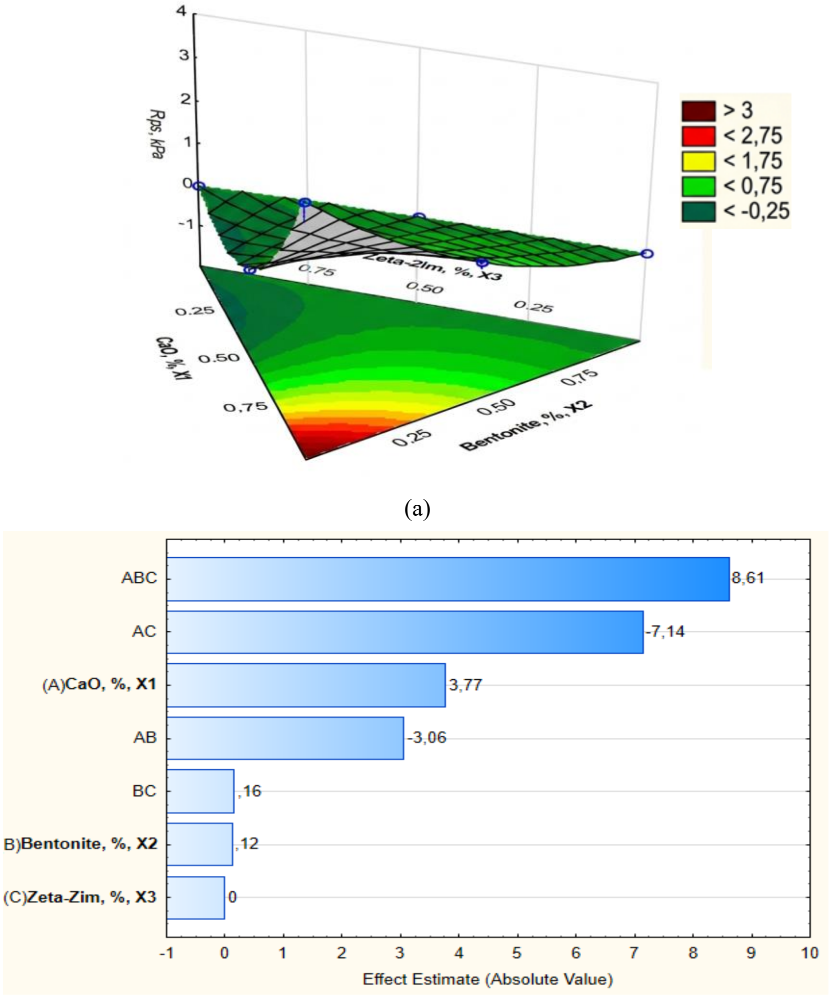
$$Ts^{21d}=57{,}86X1+0{,}8X2+1.01E^{-14}X3-68{,}36X1X2-112{,}92X1X3-1{,}12X2X3+45{,}18X1X2X3 \quad (5)$$

$$Ts^{28d}=160X1+1{,}41X2+1.05E^{-14}X3-91{,}38X1X2-314{,}04X1X3+4{,}94X2X3-198{,}87X1X2X3 \quad (6)$$

Ternary strength response surfaces (Fig. 4–6) were derived from the regression equations using the factor designations in Table 2. Point 5 as presented in Table 4 did not form sediment and was therefore assigned a value of 0. Analysis of (4)-(6) shows that plastic strength after 14, 21, and 28 days is primarily governed by factors X1, X2, and X3, which account for up to 80 % of the variation as shown in Figures 4b-6b.

Figure 4a shows that by day 14, sediment plastic strength increases from 0.1 to 3.77 kPa as a function of quicklime content (*X1*) ranging from 26.5 to 35%, the bentonite (*X2*) from 0 to 3.75% and the enzyme (*X3*) from 0 to 2%.

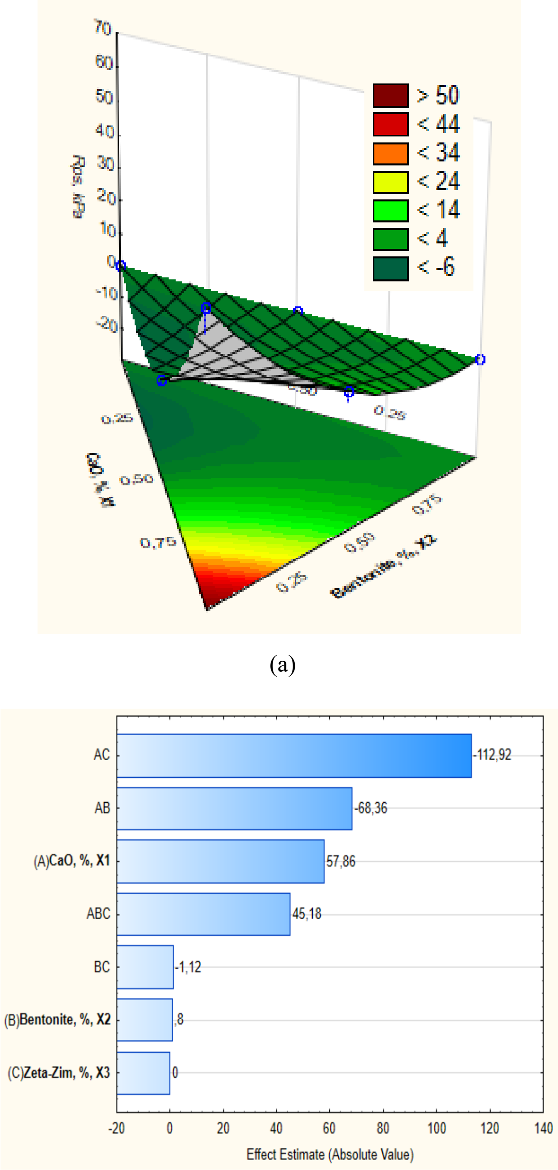
At day 21 (Fig. 5a), plastic strength rises from 0.12 to 57.86 kPa, governed by quicklime content (*X1*), ranging from 27 to 35%; the bentonite (*X2*) from 0 to 4.25%; and the enzyme (*X3*) from 0 to 2%.



(a)

(b)

Figure 4: Ternary surface: a) and Pareto diagram, b) of the influence of organo-mineral complex factors on the plastic strength of sediment after 14 days of agin.

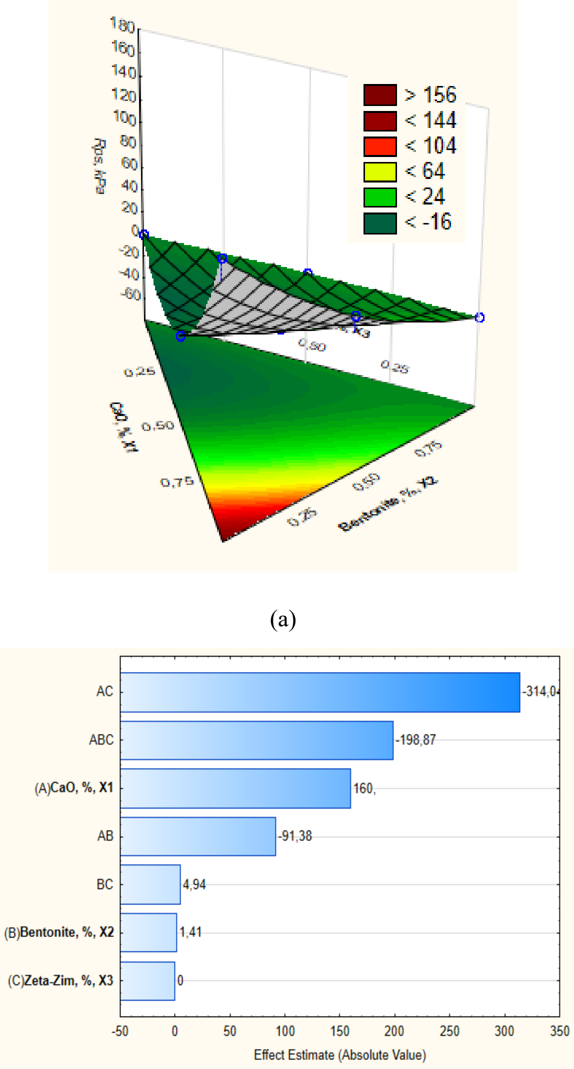


(a)

(b)

Figure 5: Ternary surface: a) and Pareto diagram, b) of the influence of organo-mineral complex factors on the plastic strength of sediment after 21 days of aging.

The maximum recorded strength of 160 kPa is attained at day 28 (Fig. 6a), with quicklime spanning 27.5–35% (*X1*), the bentonite from 0 to 5.5% (*X2*) and the enzyme from 0 to 2% (*X3*). The isolines of maximum plastic strength values are located in the lower left corner of the factor space as seen in Figures 4a-6a.



(a)

(b)

Figure 6: Ternary surface: a) and Pareto diagram, b) of the influence of organo-mineral complex factors on the plastic strength of sediment after 28 days of aging.

5 CONCLUSIONS

This study applied experimental-statistical mixture modelling to determine the optimal compositions of a bentonite–Zeta-Zim organo-mineral complex for technically polluted storage pond water, extending the reagent comparison initiated in [13].

Overlay of the three strength response surfaces at the maximum strength criterion *Ts→max*, the feasible range of the organo-mineral complex composition was determined. It is defined by quicklime content from 30 to 35% (X1), bentonite from 0 to 2.5% (*X2*) and enzyme from 0 to 1.5% (*X3*). Compositions within the range ensure the formation of artificial stone with a plastic strength of 160 kPa.

For removing turbidity (down to 1 NTU) and for forming mechanically stable sediments. Transparent water was achieved using a mixture of 2.2–4.2% quicklime, 7.5–11.25% bentonite and 6–10% enzyme. Sediments with a plastic strength of up to 160 kPa after 28 days were obtained using a mixture of 30–35% quicklime, ≤2.5% bentonite and ≤1.5% enzyme. The resulting sediment is self-compacting and waterproof, and can be used to construct embankments for storage ponds at solid waste landfills.

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