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CIRCULAR MANAGEMENT OF RUNOFF WATERS: DESIGN AND PERFORMANCE OF A FULL-SCALE TREATMENT PLANT FOR CLAY HEAP DRAINAGE

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Abstract

This study presents the conception, experimental validation, and full-scale implementation of an innovative treatment system for recovering solids from runoff waters generated by clay heaps at the SAPIR terminal in Ravenna (Italy). Runoff from open-air mineral storage areas contains high suspended solid concentrations that, if discharged untreated, can cause serious environmental degradation, increasing turbidity and sediment accumulation in surface waters. The project was developed to achieve two main objectives: (i) reducing the environmental load associated with suspended solids in effluents, and (ii) recovering and reusing the solid fraction within the ceramic industry supply chain, consistent with circular economy principles. Laboratory and pilot-scale studies were first conducted to identify an effective anionic polyelectrolyte, optimize its dosage, and assess the filtration performance of geotextile materials. Based on these investigations, the most efficient configuration, combining coagulation–flocculation with geotextile filtration was scaled up to an industrial plant designed to manage runoff from a 44,000 m² storage area. The system has a treatment capacity of 80 m³/h and operates through automated control of flow, mixing, and filtration stages to ensure stable performance under variable hydrological conditions. The full-scale plant consistently met the regulatory discharge limit of <80 mg/L total suspended solids (TSS), even during peak rainfall events. Moreover, it enabled the recovery of approximately 1,300–1,500 m³ of mineral solids annually, which were successfully reintegrated into the ceramic production chain. This approach provides measurable environmental and economic benefits by preventing solid discharges, reducing sedimentation in water bodies, and lowering the need for virgin raw materials. The Ravenna case study demonstrates how technical innovation, environmental compliance, and industrial feasibility can converge to produce a sustainable runoff treatment model. The system effectively transforms an environmental challenge into an opportunity for circular resource management, offering a replicable strategy for other port terminals and industrial storage sites.

Key words: ceramic reuse, environmental impact, geo-textile filtration, polyelectrolyte treatment, suspended solids

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1. Introduction

SAPIR is the main port terminal operator in Ravenna and plays a central role in the loading, unloading, and handling of a wide variety of goods, including ferrous and steel products, fertilizers, liquids, inert materials, and project cargo. Among these activities, the management of inert minerals such as clays and feldspars represents a substantial portion of operations, with an annual average of approximately 1.100.000 tons unloaded over the last three years.

While essential to industrial supply chains, the large-scale handling and storage of such minerals in uncovered yards inevitably gives rise to environmental challenges, particularly in relation to rainwater runoff. Precipitation events cause the leaching of fine particles, leading to runoff waters with very high concentrations of suspended solids. If released untreated, these discharges can compromise water quality, increase turbidity, affect aquatic ecosystems, and contribute to sediment accumulation in receiving channels (Bilotta and Brazier, 2008; Demir et al., 2024; Shammaa and Zhu, 2001).

In recognition of these risks, SAPIR has, since 2013, pursued a proactive strategy of improving the environmental performance of its terminal. Investments in monitoring and management systems have been directed toward mitigating the impacts of industrial activities on the surrounding environment, with particular emphasis on the water matrix. An in-depth analysis of operational practices and of the specific issues associated with the handling of minerals highlighted the critical need for decisive action in the field of wastewater management. The treatment of runoff from clay heaps became a priority both for regulatory compliance and for alignment with broader sustainability objectives.

The project described in this paper was therefore conceived with a dual aim. The first objective was to reduce the suspended solid concentration in the effluents discharged into surface waters, ensuring compliance with the legal limit of 80 mg/L imposed by Italian legislation (Legislative Decree 152, 2006). The second objective was to recover the solid fraction separated from the runoff, enabling its reuse as a raw material in the ceramic industry. This approach not only minimizes the environmental burden of discharges but also reduces the demand for virgin raw materials and avoids the disposal of valuable mineral residues, thus promoting a model consistent with circular economy principles. Similar approaches to valorizing mineral residues have been investigated in industrial and urban contexts, showing both environmental and economic benefits (Acordi et al., 2023; Yu et al., 2024).

To achieve these goals, the project followed a stepwise methodology. Laboratory investigations were first carried out to identify a suitable anionic polyelectrolyte, optimize its dosage, and evaluate the potential of geotextile-based filtration systems. The use of polyelectrolytes in wastewater treatment is well established, with applications ranging from drinking water purification to industrial effluent management (Bolto and Gregory, 2007; Bratby, 2016). In this study, their application was tailored to the specific challenge of clay-laden runoff waters. The promising results from preliminary trials led to the construction and testing of a pilot plant, which allowed verification of treatment performance under controlled yet realistic conditions. Encouraged by the successful outcomes, an industrial-scale facility was subsequently designed and realized, capable of managing runoff water from a drainage surface of approximately 44,000 m² with a treatment capacity of up to 80 m³/h.

This paper presents the development path from the initial laboratory phase to the industrial implementation, demonstrating how technical knowledge, environmental responsibility, and industrial feasibility can be combined to produce an effective treatment solution. By describing the design choices, operational parameters, and observed outcomes, the study provides evidence of both environmental and economic benefits: the prevention of significant suspended solid discharges into receiving waters and the valorization of recovered solids as a resource for the ceramic sector.

The integrated treatment approach outlined here illustrates how port terminal operators and similar facilities can transform environmental challenges into opportunities for innovation and sustainability.

2. Pilot plant description

The pilot plant was designed and constructed to reproduce, on a reduced scale, the operational conditions of runoff water treatment from clay heaps and to verify the feasibility of transferring laboratory results to a continuous system. The plant consisted of four main sections: a loading and homogenization unit for the runoff water, a polyelectrolyte preparation system, a reactor for mixing, and a final filtration section. This configuration allowed the simulation of the entire treatment process, from collection of raw effluent to the production of clarified water and separated solids. The loading and homogenization section was developed to ensure the representativeness and stability of the influent. Runoff water collected from the clay piles was stored in a dedicated tank, where continuous mixing was performed to achieve uniform distribution of suspended solids before treatment. Fig. 1(a) illustrates the homogenization tank used during the experimental phase, while Fig. 1(b) shows the mixing of the effluent. Proper homogenization was considered essential to guarantee reliable downstream reactions with the polyelectrolyte and to avoid localized variations in solid concentration that could compromise treatment efficiency.

Figure 2 illustrates the key functional units of the pilot plant. In particular, Fig. 2(a) shows the polyelectrolyte preparation system, designed to accommodate both solid and liquid formulations. This flexibility allowed comparative testing under controlled conditions to determine the most appropriate type of coagulant for treating runoff water rich in clay particles. Figure 2(b) depicts the reactor, where the mixing between the effluent and the prepared polyelectrolyte solution occurs.

The reactor was constructed as a pipeline system, in which parameters such as pipe length, internal diameter, and the number of bends played a decisive role in ensuring sufficient turbulence and contact time for efficient flocculation. Proper mixing was essential to guarantee the rapid aggregation of fine suspended particles into larger flocs that could later be retained during filtration. The first series of laboratory-scale tests carried out on the pilot plant focused on defining the optimal dosage of polyelectrolyte required to achieve effective separation. Two different formulations were evaluated: a solid polyelectrolyte and a liquid one.

(a) (b)

Fig. 1. Homogenization facility used during pilot testing: (a) storage and homogenization tank for collecting runoff water from clay heaps; (b) mixing process of the effluent to ensure uniform homogenization prior to treatment in the reactor

(a) (b)

Fig. 2. Pilot plant units: (a) polyelectrolyte preparation system, allowing the use of solid or liquid formulations; (b) reactor where the runoff water and polyelectrolyte are mixed, with pipeline length, diameter, and bends influencing mixing efficiency

Although the solid form showed good coagulation performance, its hygroscopic nature made it highly sensitive to ambient humidity, complicating both storage and dosing operations. The liquid polyelectrolyte, on the other hand, was easier to handle and dose with greater precision, but its properties were influenced by temperature fluctuations. Given these considerations, the liquid formulation was ultimately selected as the most reliable solution for scaling up the process. To mitigate the temperature sensitivity of the liquid product, both the reactor and the storage tanks for the polyelectrolyte were fully insulated during construction. This design measure ensured stable conditions and consistent treatment efficiency, laying the groundwork for the subsequent development of the full-scale industrial plant.

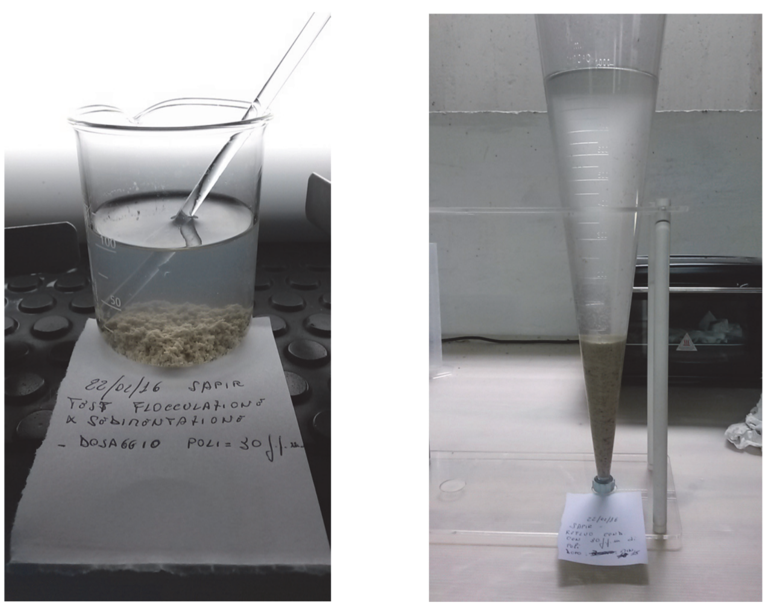
3. Analyzing of results

To reproduce the conditions of runoff from clay heaps, a synthetic water–clay suspension with a concentration of 30 g/L was prepared and subjected to a series of laboratory and pilot-scale tests. This concentration corresponded closely to the typical solids load observed in actual runoff from uncovered yards at the terminal. The primary goal of the experiments was to determine the effective dosage range of anionic polyelectrolyte required to promote rapid flocculation and efficient separation of suspended solids.

Figure 3(a) shows the flocculation process, showing the formation of compact sludge flakes after the addition and mixing of the polyelectrolyte with the clay-laden water. The creation of dense, well-structured flocs confirmed the effectiveness of the selected polymer in aggregating fine particles. Figure 3(b) presents the Imhoff cone test used to assess sedimentation performance. The main physicochemical characteristics of the water–clay mixture and the applied treatment conditions are summarized in Table 1, which shows neutral pH (7.35), suspended solids concentration of 8 g/L, and an initial polyelectrolyte dosage of 30 mg/L.

Sedimentation behavior was monitored over time, as reported in Table 2. The results indicate that solids settled very rapidly: within 10 minutes, most of the suspended matter had already deposited, reaching a sedimented volume of 80 mL from the initial charge. Beyond this point, only marginal compaction occurred, with the volume stabilizing at 72 mL after 40 minutes. These findings demonstrate that a settling period of about 10 minutes is sufficient for effective clarification, and extended sedimentation yields only limited additional benefit. The test confirmed that the combination of the selected anionic polyelectrolyte and the runoff water matrix provides favorable conditions for fast and stable separation. Comparable rapid settling behavior after polymer-assisted coagulation has been reported in other studies addressing fine mineral suspensions, highlighting the effectiveness of anionic polyelectrolytes in promoting fast flocculation and sedimentation (Bolto and Gregory, 2007; Bratby, 2016). Following the optimization of coagulation and sedimentation, attention was turned to the solid–liquid separation step. Commercially available filter types were tested, but failed to guarantee effluent quality below the discharge limit of 80 mg/L total suspended solids (TSS). For this reason, geotextile-based filtration was investigated.

Two different fabrics, each with stable warp and weft structure, were examined under varying polyelectrolyte concentrations. The results are summarized in Table 3**.** At a polyelectrolyte dose of 30 mg/L, the black geotextile produced permeate with a TSS of 59 mg/L and low residual concentrations of aluminum (0.50 mg/L) and iron (0.089 mg/L), well below the respective regulatory thresholds. By contrast, the grey geotextile was markedly less effective, yielding much higher TSS (220 mg/L) and elevated metals. At reduced dosages (10–20 mg/L), the black fabric still showed better performance, though the TSS exceeded the legal limit when under-dosing occurred (140 mg/L at 10 mg/L poly). These results confirmed the superiority of the black geotextile, provided that adequate polyelectrolyte dosage was maintained. The black fabric was therefore selected for subsequent trials, supported by its favorable mechanical properties: longitudinal tensile strength of 130 kN/m, transverse tensile strength of 80 kN/m, porometry of 110 µm, and a static punching resistance of approximately 4000 N. Based on these properties, a first Geo tube was manufactured and installed in the pilot plant. Figure 4(a) shows the constructed Geo tube and the feeding line transporting the polyelectrolyte–water mixture from the reactor, while Fig. 4(b) depicts the discharge of clarified water after filtration through the geotextile.



(a) (b)

Fig. 3. Laboratory tests for evaluating polyelectrolyte performance: (a) formation of compact sludge flocs after mixing the runoff water with the polyelectrolyte; (b) Imhoff cone test illustrating sedimentation behavior of the treated mixture

Table 1. Characteristics of the clay–water mixture and operating parameters used during laboratory tests for polyelectrolyte dosage optimization

Characteristics	***Units***	***Value***
Mixture characteristics		
pH		7.35
Solid weight	kg/L	1
Suspended solids	g/L	8
Polyelectrolyte		
kind		Anionic
Concentration	mg/L	30
Settling time (90%)	min.	10

Table 2. Results of the Imhoff sedimentation cone test, showing the variation of sedimented volume over time for the treated clay–water mixture

Time	min	0	3	5	**10**	15	20	25	30	40	60
Sediment volume	mL	1000	100	90	**80**	78	75	74	74	72	72

Table 3. Results of geotextile filtration tests conducted with different polyelectrolyte concentrations, showing the effects on total suspended solids (TSS) and residual concentrations of aluminum (Al) and iron (Fe) compared with legal discharge limits

Test	***Geotextile***	***Polyelectrolyte concentration***	***TSS***	***AL***	***FE***
			mg/L	***mg/L***	***mg/L***
Legal limit			**80**	1	2
1	Black	20	**55**	0.51	0.12
2	Grey	30	**220**	1.5	0.37
3	Black	30	**59**	0.5	0.089
4	Black	10	**140**	1.8	0.34

The functional pilot test was performed in automatic mode, treating 25 m³ of runoff water stored in the homogenization tank. The experiment lasted approximately six hours, with a single-screw pump delivering a flow rate of 680–850 L/h. The optimal dosage of the anionic polyelectrolyte was determined to be in the range of 60–70 mg/L. Under these conditions, the filtrate was consistently clear and free of settleable solids, as confirmed by additional Imhoff cone tests. The Geo tube was filled without structural problems, maintaining a maximum operating pressure of ~0.3 bar. Special care was given to construction details, including the diameter and orientation of the inlet pipe and the number and sealing of seams, as these factors proved crucial for uniform filling and mechanical stability.

Figure 5 summarizes the complete treatment cycle observed in the pilot plant: stage (1) runoff water containing clay, stage (2) post-reaction mixture after polyelectrolyte addition, stage (3) solid fraction retained within the Geo tube, and stage (4) clarified effluent released from the system.

(a) (b)

Fig. 4. Pilot plant filtration system: (a) Geo tube constructed and connected to the pipeline for feeding the polyelectrolyte–water mixture exiting the reactor; (b) discharge of clarified water after filtration through the geotextile

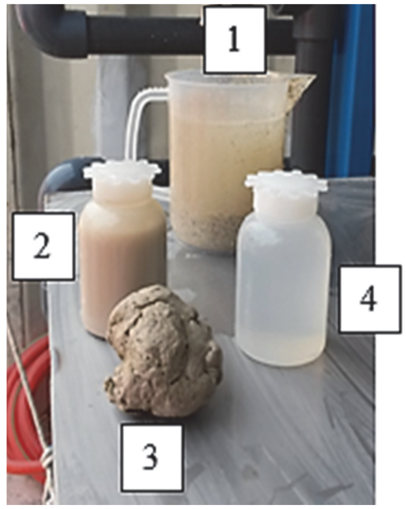


Fig. 5. Complete treatment cycle of the pilot plant: (1) runoff water containing clay; (2) post-reaction mixture with polyelectrolyte; (3) solid fraction retained in the Geo tube; (4) clarified effluent discharged after filtration

Both the preparation of the polyelectrolyte solution and the transfer of homogenized runoff water from the storage tank into the reactor were fully automated, ensuring regular and continuous operation. Inside the reactor, the polyelectrolyte interacted with the clay suspension to form sludge flocs, which were subsequently trapped by the geotextile, while the filtrate was discharged to the sewer. The pilot-scale results provided strong evidence for the technical feasibility and efficiency of the system, enabling the scale-up to an industrial facility. Based on rainfall data recorded over the past decade, including extreme events, the industrial plant was dimensioned to manage an annual precipitation of 626 mm. Accordingly, a 600 m³ storage tank and an inlet flow capacity of 80 m³/h were established to ensure compliance with discharge regulations while maintaining robustness under variable hydrological conditions. Similar applications of geotextile dewatering have demonstrated comparable performance in treating fine-grained sediments and sludge, confirming their robustness and adaptability to different industrial scenarios (Accordi et al., 2023; Aparicio Ardila et al., 2020). Moreover, the integration of recovered solids into industrial reuse pathways, such as construction or ceramics, is consistent with circular economy principles promoted in recent studies on mineral residue valorization (Choudhury et al., 2021; López et al., 2018).

The long-term operating data of the industrial plant provide important insights into both its technical reliability and its environmental contribution. Figure 6 presents the annual operating hours of the treatment system, which varied significantly across different years. This variability is strongly correlated with rainfall patterns: years with higher precipitation required more extensive system operation to manage increased runoff volumes, while drier years resulted in reduced operating times. Such dependence on climatic variability is typical for runoff treatment systems and highlights the need for robust design capable of handling both average and extreme conditions. The results confirm that the adopted configuration, sized based on ten years of rainfall records, was sufficient to ensure compliance with discharge requirements under all operational scenarios.

In addition to operational stability, the system demonstrated significant potential for resource recovery. Figure 7 shows the estimated quantity of material recovered annually, which ranged between 1.270 and 1.450 m³. This consistent recovery rate reflects the ability of the combined coagulation–flocculation and geotextile filtration process to capture fine clay particles efficiently. From an environmental perspective, this represents a direct benefit by preventing the release of suspended solids into receiving waters, thereby reducing turbidity and protecting aquatic ecosystems.

From an economic and industrial perspective, the recovery of this solid fraction allowed reintegration into the ceramic supply chain, reducing the demand for virgin raw materials and lowering the costs associated with waste disposal. The dual outcomes evidenced in Figs. 6 and 7, compliance with stringent water quality standards and the generation of a reusable secondary raw material highlight the broader implications of this work. The case study demonstrates how environmental challenges associated with industrial runoff can be transformed into opportunities for sustainable resource management. Similar experiences reported in the literature support these findings: geotextile dewatering systems have been successfully employed for fine sediments and sludge (Aparicio Ardila et al., 2020; Yee et al., 2012), and the valorization of mineral residues in industrial applications has been recognized as a key strategy for advancing the circular economy (Cisternas et al., 2022; Yu et al., 2024).

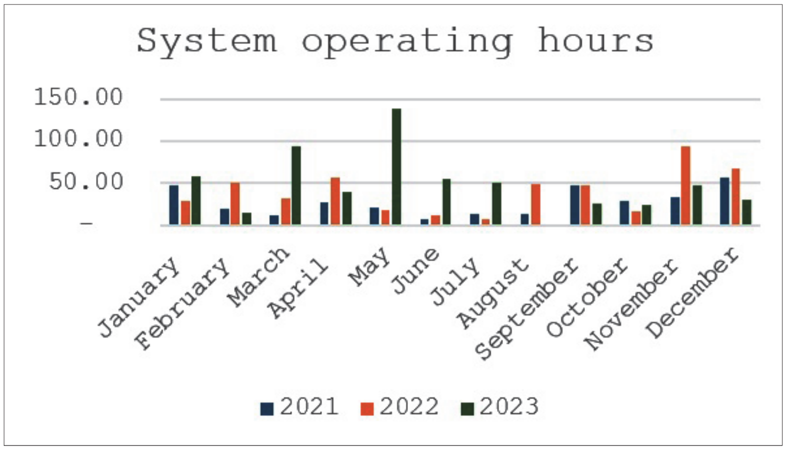


Fig. 6. Operating hours of the treatment system over different years, highlighting variations in activity linked to rainfall trends and seasonal runoff patterns

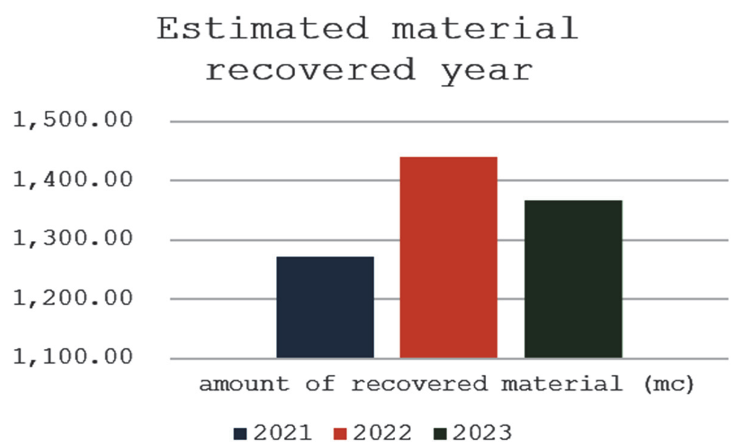


Fig. 7. Estimated annual quantity of material recovered by the industrial plant, showing the contribution of the treatment system to resource recovery and circular reuse in the ceramic sector

4. Industrial plant

The successful outcomes of the pilot-scale trials provided the technical basis for the design and implementation of the industrial-scale treatment system. The industrial plant was conceived to manage runoff generated from a total drainage area of 44,000 m², corresponding to the uncovered yards used for the storage of clay and other inert materials. The design criteria were established on the basis of ten years of rainfall data, with particular attention given to extreme precipitation events. This ensured that the system would be capable of maintaining compliance with regulatory limits even under unfavorable hydrological conditions.

Figure 8 presents the flow chart of the reaction and treatment system. The diagram highlights the sequential stages, beginning with the collection and homogenization of runoff water, followed by chemical conditioning with anionic polyelectrolyte, mixing in the reactor, and final filtration through geotextile-based Geo tubes. During the design phase, the possibility of incorporating two parallel treatment lines was carefully considered. This redundancy was evaluated as a safeguard to ensure continuous operation during routine maintenance or in case of system malfunctions. The adoption of parallel lines would guarantee that effluent quality remains compliant at all times, even under conditions of increased hydraulic load or partial system unavailability. This reflects a common industrial strategy, where redundancy is built into water treatment infrastructure to enhance resilience and minimize operational risks.

Figure 9 provides a detailed layout of the industrial treatment facility. The system is composed of four pumps dedicated to filling the 600 m³ storage basin, two mixers inside the basin to maintain homogeneous suspension of the incoming runoff water, and two progressive cavity pumps that transfer the water from the basin to the reactor. At the reactor outlet, the system includes four control valves that regulate the flow to the Geo tubes, ensuring balanced loading and preventing excessive stress on individual units. In addition, one valve is dedicated to directing clarified water for reuse, while another manages discharge to the wastewater system when required. The inclusion of multiple pumps and valves provides operational flexibility, allowing the plant to adapt to variable inflow conditions and to optimize treatment efficiency. The design of the industrial plant emphasizes robustness and adaptability. The drainage system ensures that all runoff water is effectively collected and conveyed to the storage tank, where continuous mixing prevents sedimentation and ensures a representative feed to the reactor. The maximum operating flow rate of 80 m³/h was selected to balance hydraulic capacity with treatment efficiency, ensuring sufficient residence time for flocculation reactions and reliable solid–liquid separation in the Geo tubes.

The use of progressive cavity pumps is particularly advantageous in this context, as they are well suited to handling viscous, particle-laden suspensions without causing shear that could break down flocs. From an industrial perspective, the system demonstrates several important applications. First, it ensures regulatory compliance by consistently reducing suspended solids concentrations in the effluent below 80 mg/L, as required by Italian legislation for discharge into surface waters. Second, it provides an environmentally sustainable solution by preventing the release of fine clay particles that could otherwise cause turbidity and ecological impacts in receiving channels. Third, it enables resource recovery by concentrating the solid fraction in Geo tubes, from which it can be extracted and reintegrated into the ceramic industry supply chain.

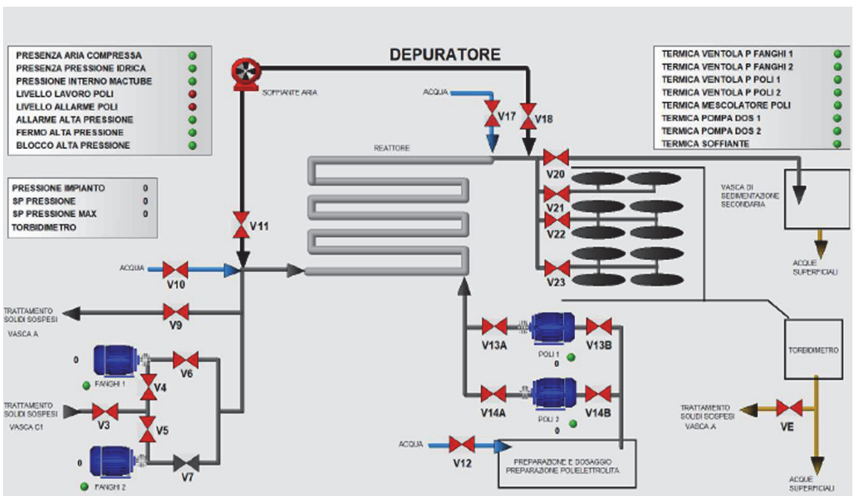


Fig. 8. Flow chart of the reaction and treatment system, illustrating the main stages of runoff water management, from collection and storage to mixing with polyelectrolyte, reaction in the reactor, and subsequent filtration through the Geo tube

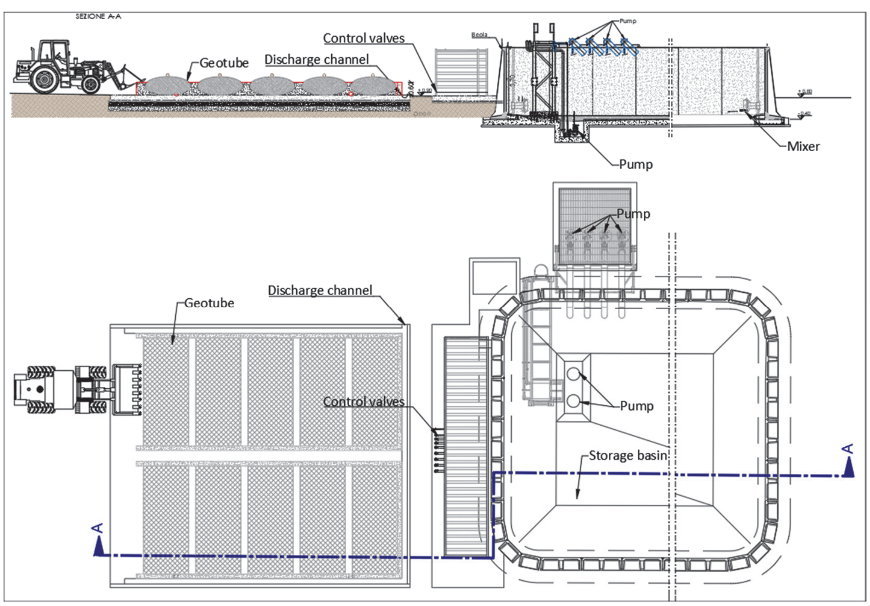


Fig. 9. Layout of the industrial treatment system, showing the storage basin, mixers, pumps for transferring runoff water to the reactor, control valves for effluent management, and the Geo tube units for solid-liquid separation

This represents a clear example of circular economy practice, where what would otherwise be treated as waste is converted into a usable secondary raw material. The system also provides operational benefits in terms of flexibility and resilience. The presence of multiple pumps, mixers, and control valves allows plant operators to adjust treatment rates according to rainfall intensity, storage tank levels, and seasonal variations. In the event of equipment failure or during scheduled maintenance, flow can be redirected, and the system can continue operating without interruption. This level of reliability is critical in port terminal operations, where large volumes of runoff water can be generated in short periods during storm events.

In broader industrial practice, the design principles demonstrated here robust hydraulic capacity, redundancy for reliability, integration of chemical conditioning and geotextile dewatering, and valorization of recovered solids can be applied to a wide range of contexts. These include other port terminals handling mineral cargoes, mining operations, and industrial storage yards where runoff waters carry high suspended solids loads. The Ravenna case study illustrates how such systems can simultaneously address environmental compliance, operational reliability, and resource efficiency, thereby contributing to sustainable industrial management.

5. Conclusions

This work described the complete pathway from laboratory investigation to pilot-scale validation and industrial implementation of a treatment system for the recovery of solids from clay heap runoff at the SAPIR terminal in Ravenna. The results clearly demonstrate that the combined use of anionic polyelectrolytes and geotextile-based filtration offers a robust, efficient, and transferable solution for managing runoff waters with high suspended solid loads.

Laboratory tests confirmed the effectiveness of the selected polyelectrolyte in promoting rapid flocculation and sedimentation of fine clay particles, with most solids settling within 10 minutes. Pilot-scale trials further validated the feasibility of the approach, optimizing polyelectrolyte dosage and confirming the superior performance of the black geotextile for solid–liquid separation. The pilot plant provided reliable data that guided the design of the industrial system.

At full scale, the plant was designed to manage runoff from a 44,000 m² drainage area with a treatment capacity of 80 m³/h, supported by a 600 m³ storage basin and a resilient pumping and mixing system. Long-term operational data showed stable performance under variable rainfall conditions, with annual operating hours closely reflecting precipitation trends.

Importantly, the system not only ensured compliance with discharge limits (<80 mg/L TSS) but also enabled the recovery of approximately 1,300–1.500 m³ of solids each year. These solids were successfully reintegrated into the ceramic industry, reducing waste disposal needs and lowering the demand for virgin raw materials.

The dual benefits of the system, environmental protection through improved water quality and economic gain through resource recovery, highlight its contribution to sustainability and circular economy objectives. The Ravenna case study provides a replicable model for other port terminals, mining sites, and industrial storage areas facing similar challenges. The integration of technical reliability, environmental responsibility, and industrial feasibility illustrates how targeted investments in wastewater management can transform environmental pressures into opportunities for innovation and sustainable resource use.

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