OPTIMIZING THE PHOSPHORUS SLAG REFINING PROCESS AND ITS POTENTIAL APPLICATION AS A HIGH-GRADE FUNCTIONAL FILLER: A SOLUTION TO THE CIRCULAR ECONOMY PROBLEM

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Abstract. The rapid expansion of the chemical industry, specifically elemental phosphorus production in the Tang Loong Industrial Park (Lao Cai, Vietnam), presents significant ecological challenges, generating approximately 667,800 tons of hazardous slag annually. Chemically, phosphorus slag (PS) is rich in calcium silicate, primarily composed of CaO (50–52 wt%) and SiO_2 (37–40 wt%), presenting substantial opportunities for secondary valorization. However, the presence of residual soluble impurities acts as a significant technical barrier, impeding hydration kinetics and limiting the material's compatibility in high-value applications.

To address these limitations, this study developed an integrated purification protocol combining gravity separation and chemical washing to recover high-purity slag powder. The refined mineral powder was subsequently evaluated as a functional filler across three material matrices: protective coatings, high-density polyethylene (HDPE) composites, and wall putty formulations. Experimental results indicated an optimal slag-to-resin mass ratio of 1.25:1 for the coating system, yielding excellent adhesion and an opacity of up to 99%. In the HDPE matrix, filler loadings between 5 wt% and 20 wt% preserved elongation properties while significantly enhancing tensile strength. For cementitious applications, the slag-modified wall putty achieved adhesion strengths exceeding 0.8 N/mm², substantially surpassing the requirements of the TCVN 7239:2014 standard.

These findings demonstrate that with appropriate physicochemical treatment, phosphorus slag can effectively substitute natural mineral fillers, thereby promoting sustainable resource management within the construction and materials sectors.

Keywords. Phosphorus slag; Circular economy; High - density polyethylene (HDPE) composites; Refined material; Tang Loong industrial park.

1 INTRODUCTION

The rapid intensification of elemental phosphorus production in developing economies has precipitated a critical environmental challenge concerning solid waste management. A pertinent case is the Tang Loong Industrial Park (Lao Cai, Vietnam), where the production of one ton of elemental phosphorus (P4) generates approximately 8-10 tons of slag. Consequently, the region accumulates over 667,000 tons of this hazardous by-product annually [1]. The slag, generated via medium-scale electric furnace technology using apatite ore, quartzite, and graphite electrodes [2], is typically quenched from temperatures of 1400-1500°C. This process yields an amorphous calcium-silicate glass matrix primarily composed of pseudo-wollastonite ($CaSiO_3$) and rankinite ($Ca_3Si_2O_7$) [3], with a chemical profile dominated by CaO (50-52%) and SiO_2 (37-40%) [4].

However, the valorization of this material is significantly hindered by the presence of deleterious impurities, specifically soluble phosphates (P_2O_5, 1-1.5% wt%) and fluorides (F^-, 0.5-1% wt%). Recent mechanistic studies by Zhuang et al. (2025) and Shan et al. (2025) demonstrate that soluble phosphorus ions readily form insoluble calcium phosphate coats on hydrating cement grains, severely retarding hydration kinetics and suppressing early strength development [5, 6]. While traditional recycling pathways have focused primarily on low-grade supplementary cementitious materials (SCMs) or road sub-base aggregates, these low-value applications fail to offset processing logistics and do not fully exploit the intrinsic mineralogical quality of refined calcium silicate [7, 8].

In the context of material cycles, phosphorus slag (PS) possesses latent hydraulic properties and physicochemical characteristics comparable to commercial mineral fillers, such as a specific gravity of ~2.75 g/cm^3, high compressive strength (80-100 MPa), and low water absorption [9]. Existing literature has extensively explored PS as a supplementary cementitious material (SCM) or aggregate in road subbases

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and unfired bricks [10, 11]. Nevertheless, a major technical barrier persists: soluble phosphorus and fluorine compounds severely retard the hydration kinetics of Portland cement, often limiting the mechanical development to low-grade applications (e.g., PC20) [5, 12]. Furthermore, the lack of effective purification technologies has restricted PS utilization to low-value construction aggregates, failing to address the projected shortages of high-quality mineral fillers in the polymer and coating industries.

Simultaneously, global industrial sectors face acute shortages and rising costs of conventional mineral fillers (e.g., ground calcium carbonate, talc, and kaolin) and functional pigments (e.g., rutile TiO2). As shown in Table 1, industrial demand for high-purity mineral fillers across polymer compounding, protective coatings, and dry-mix construction systems is expanding rapidly [11]. Bridging the gap between industrial waste mitigation and high-grade filler demand requires an integrated "waste-to-resource" strategy.

Table 1. Projected demand and technical role of functional mineral fillers across major industrial sectors

Industrial Sector	Projected Annual Demand	Key Technical Requirements for Fillers	Primary References (Updated)
Plastics and Rubber	≈2.5 million tons/year	High dispersion, low oil absorption, high tensile/elongation retention	[13], [12]
Protective Coatings	≈250 thousand tons/year	Opacity, particle fineness (<10 μm), optical whiteness (≥85%)	[14], [15]
Dry-Mix Mortars and Putty	>30 million tons/year	High adhesion strength (>0.5 N/mm^2), water retention, chemical stability	[7], [16]
Cement and Concrete	>150 million tons/year	Controlled setting, hydraulic reactivity, low impurity leaching	[5], [6]

In this study, a multi-stage physico-chemical beneficiation scheme integrating chemical washing, gravity separation, and fine mechanical grinding was developed to purify raw PS. The refined slag was systematically evaluated as a functional substitute for commercial fillers across three high-value applications: organic polyurethane/acrylic coatings, High-Density Polyethylene (HDPE) thermoplastic composites, and polymer-modified wall putty formulations. By elucidating the performance mechanisms of treated PS within these diverse matrices, this research establishes a scientifically rigorous foundation for the industrial-scale upcycling of phosphorus slag, effectively mitigating environmental burdens while fostering sustainable resource efficiency.

2 MATERIALS AND METHODS

2.1 Materials – Chemicals

Raw Phosphorus Slag: The raw phosphorus slag (PS) used in this investigation was procured from the Nam Tien Company (Lao Cai Province, Vietnam), a major industrial facility for elemental phosphorus production. The slag is a by-product of the electro-thermal reduction of apatite ore, quartzite, and coke at temperatures of 1400-1500 °C. Upon rapid water quenching, the molten slag solidifies into a vitreous, grayish-white granular material dominated by amorphous calcium silicate phases. Physical characterization revealed a heterogeneous particle distribution with an average grain size of approximately 2 mm and a bulk specific gravity of 2.75 g/cm^3. Based on density and morphology, the slag comprises three distinct phases. The dominant fraction, constituting over 90% of the total mass, consists of polygonal particles with a specific gravity of ~2.51 g/cm^3, primarily composed of pseudo-wollastonite ($CaO{\cdot}SiO_2$) and rankinite ($3CaO{\cdot}2SiO_2$). A minor fraction (0.2-0.5%) comprises spherical particles, predominantly Ca_3SiO_5, exhibiting a lower specific gravity of ~2.05 g/cm^3. The remaining 2-4% consists of metallic inclusions and ferrophosphorus compounds with a significantly higher density of ~4.02 g/cm^3. Chemical analysis further indicated the presence of deleterious impurities, including soluble phosphorus pentoxide (P_2O_5), residual

fluorides, and carbonaceous matter from electrode erosion, necessitating purification prior to application. The moisture content of the as-received slag was consistently maintained below 1%.

Chemical Reagents and Matrix Materials: To remove soluble impurities and refine the slag, a specific set of industrial-grade reagents was employed. Calcium oxide (CaO) and hydrated lime ($Ca(OH)_2$) served as precipitating agents to convert soluble phosphates into insoluble calcium phosphates, while anionic polyacrylamide (PAM) and protein-based agents were use as flocculants.

For coating formulations, solvent-based systems were prepared using an acrylic polyol resin (HSU 1908) cured with a polyisocyanate hardener (Desmodur N75) in xylene, whereas water-based systems used a waterborne acrylic emulsion (R4322) with AM-95 as a pH regulator. Rutile titanium dioxide (TiO_2, R902) was employed as the reference pigment. The polymer matrix for thermoplastic composites consisted of High-Density Polyethylene (HDPE) resin (Melt Flow Index: 1.20 g/10 min; density: 0.937 g/cm^3). For wall putty formulations, the binder system comprised White Portland Cement (PCW30) and Grey Portland Cement (PCB30) conforming to Vietnamese standards, modified with polyvinyl alcohol (PVA) powder (DA1120) to enhance workability and interfacial adhesion.

2.2 Methods

Slag Purification and Specimen Fabrication: The experimental protocol commenced with the purification of raw phosphorus slag via a physical separation process designed to exploit the specific gravity differentials between amorphous silicates, metallic inclusions, and carbonaceous particles. The processing line integrated a two-layer wet vibrating screen for preliminary size classification, followed by a gravity shaking table to concentrate the target silicate fraction. To ensure environmental compliance and resource efficiency, the water supply system was equipped with chemical dosing pumps, sedimentation tanks, and decantation units, enabling a continuous closed-loop circulation. Following purification, the refined slag was comminuted to a particle size of less than 74 μm using a mechanical grinder. For the fabrication of application-specific composites, high-speed mechanical mixers were employed to disperse the filler in coating formulations, while a twin-screw compounder coupled with a hydraulic press was utilized to process and mold the HDPE-slag composites.

Characterization Techniques: To comprehensively evaluate the physicochemical evolution of the slag and the performance of the resulting composites, a multi-faceted analytical approach was adopted. The chemical composition and crystalline phase assemblages were determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD), respectively. Concurrently, microstructural morphology and surface elemental distribution were examined via scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX), a combination widely cited in phosphorus slag valorization studies [2, 4, 5]. Furthermore, the macro-mechanical and physical properties-including particle size distribution, specific gravity, water absorption, compressive strength, and flexural strength-were quantified in strict adherence to Vietnam National Standards (TCVN) and technical regulations. Specifically, the testing protocols aligned with QCVN 16:2017/BXD for mineral admixtures, TCVN 6016 for cement mortar strength, and TCVN 8264 for the general mechanical properties of construction materials [10, 6].

2.3 Experimental Procedure

Purification and Powder Preparation: The valorization protocol commenced with the beneficiation of raw phosphorus slag via a hydraulic washing-gravity separation circuit, designed to exploit the specific gravity differentials between the target silicate phase and deleterious heavy impurities. During the screening and shaking table stages, the system operated with a continuous injection of process water pre-saturated with Calcium Hydroxide ($Ca(OH)_2$). This chemical intervention facilitated the in-situ precipitation and subsequent removal of soluble phosphate compounds (P_2O_5), fluorides, and carbonaceous electrode residues [2,14]. Following the separation phase, the purified silicate fraction was desiccated and comminuted to a fineness passing a 74 μm sieve. The physicochemical properties of the resulting powder were rigorously validated against the Vietnamese technical regulation QCVN 16:2017/BXD to ensure its suitability as a mineral admixture [10].

Formulation and Performance Evaluation: Upon establishing compliance, the refined slag was integrated into three distinct industrial formulations to assess its versatility as a functional filler. In the domain of construction finishing materials, the slag was utilized in wall putty formulations, substituting 70-80% of conventional carbonate fillers. For thermoplastic applications, composite specimens simulating HDPE corrugated pipes were fabricated via melt-blending with slag loadings ranging from 5 to 20 wt%. Concurrently, in surface coating technology, both solvent-based and waterborne paint systems were formulated with slag-to-resin weight ratios varying from 0.5:1 to 1.5:1. The performance characteristics of these slag-incorporated end-products were subsequently evaluated strictly following sector-specific standards, specifically TCVN 7239:2014 for wall putty adhesion, TCVN 8789:2011 and ISO 2409 for coating durability, and TCXDVN 272:2002 for the mechanical integrity of HDPE pipes. Comparative assessments were conducted against control samples containing traditional commercial fillers (limestone, kaolin) to quantify the specific performance enhancements attributed to the refined slag [13,12].

3 RESULTS AND DISCUSSION

3.1 Quality of processed phosphorus furnace slag product

The phosphorus slag, after undergoing washing, gravity separation, and grinding, forms a grayish-white powder with a relatively uniform particle distribution (Figure 1A). Scanning electron microscopy (SEM) reveals that the treated material consists of irregular polygonal particles (Figure 1B), which are characteristic of mechanically fractured amorphous calcium silicate matrices. These morphological observations are consistent with the findings of He et al. and Yang et al. regarding phosphorus slag processed via wet milling and physical purification [9, 15].

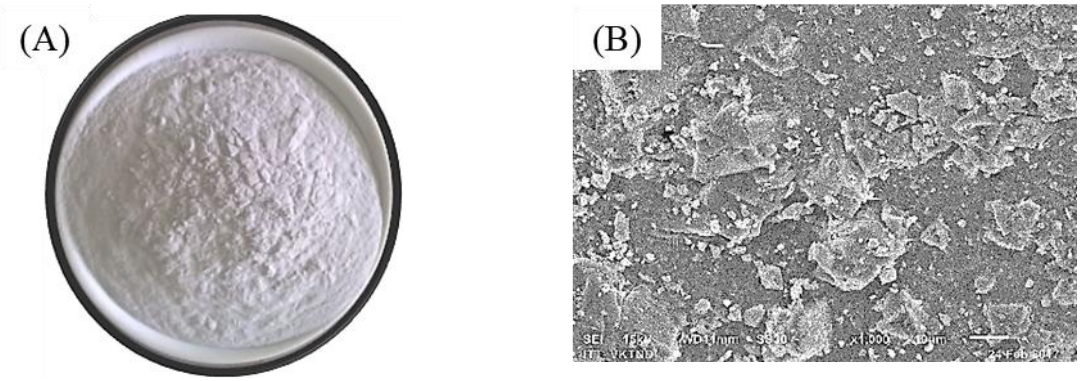


Figure 1. Morphological characterization of phosphorus slag post-treatment: (A) Refined grayish-white powder (D50<15 μm); (B) SEM micrograph depicting fractured, irregular polygonal calcium silicate particles (1000× magnification).

Chemical composition analysis (Table 2) and X-ray diffraction (XRD) patterns (Figure 2) confirm a substantial improvement in slag purity following the treatment. The XRD results indicate that the dominant phase in the treated slag is pseudo-wollastonite ($Ca_3(SiO_2)O$), whereas the crystalline peaks corresponding to $Ca_2P_2O_7$, FeP, and MgO-which were present in the original slag-are significantly reduced. Furthermore, the absence of precipitates such as $CaHPO_4$, $CaSO_4.2H_2O$, and residual graphite demonstrates the effective removal of soluble and carbonaceous impurities. This phase refinement aligns with studies by Yong et al. and Hu et al., which emphasize that eliminating P- bearing and F-bearing phases is critical for optimizing slag compatibility in construction applications [16, 6].

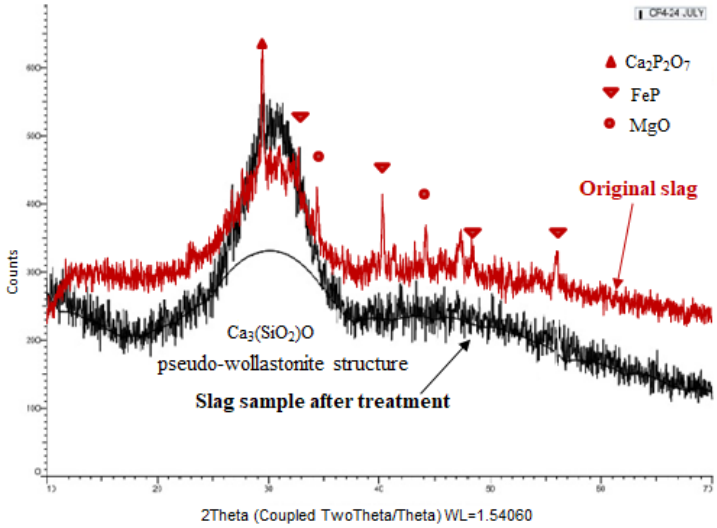


Figure 2. Powder X-ray diffraction (XRD) pattern of refined phosphorus slag highlighting dominant pseudo-wollastonite ($Ca_3(SiO_3)^3$) phases and minimal impurity peaks.

The quantitative chemical results are presented in Table 2. Post-treatment, the whiteness of the slag increased from ≥80 to ≥85, rendering it suitable for applications in paint and filler systems. Notably, the dissolved P_2O_5 content decreased dramatically from ≤1.5% to ≤0.10%, and total metal oxide impurities (Fe_3O_4, MnO, MgO, TiO_2) were reduced from 5.0-7.0% to 1.5-3.0%, thereby confirming the effectiveness of gravity separation. Heavy metal concentrations (Pb, Cd, As) remained strictly below permissible thresholds. Additionally, the natural radioactivity index exhibited a slight decrease from ~0.85 to ~0.70, maintaining compliance with national safety limits for non-structural building materials [6].

Table 2. Chemical composition of phosphorus slag samples before and after treatment

Parameter / Indicator	Unit	Raw Slag (As-Received)	Refined Slag Powder	Commercial Limestone Control	Testing Standard / Method
Whiteness	%	80.0±1.2	85.5 ± 0.8	95.0 ± 0.5	TCVN 10563:2014
Density	g/cm^3	2.57	2.57	2.70	Pycnometer
CaO Content	wt%	38.0 - 45.0	38.0 - 45.0	50.0 - 55.0	XRF Analysis
SiO_2 Content	wt%	38.0 - 45.0	38.0 - 45.0	<0.20	XRF Analysis
Soluble P_2O_5	wt%	≤1.50	≤0.10	-	Photometric
Soluble F^-	wt%	≤0.50	≤0.05	-	Ion Chromatography
Impurity Oxides	wt%	5.0–7.0	1.5 - 3.0	< 0.5	XRF Analysis

Importantly, while trace amounts of phosphorus and fluorine remain, they are predominantly incorporated into the stable calcium silicate glass network. This structural integration significantly reduces their reactivity and leaching potential, a stabilization mechanism corroborated by Hu et al., who identified the encapsulation of residual P and F within amorphous glass matrices in phosphorus slag-based binders [6].

Collectively, these findings demonstrate that the treated slag powder fulfills the essential technical requirements to replace limestone powder and other mineral fillers in various product formulations, including paints, polymers, and dry-mix mortars. Furthermore, the enhanced whiteness, improved chemical stability, and diminished impurity levels significantly elevate its value as an eco-friendly industrial raw material [14].

3.2 Applications of treated phosphorus slag

3.2.1. Paint preparation using phosphorus slag powder

Mineral fillers are widely used in the paint industry to enhance coverage, adjust rheological behavior, and reduce formulation costs. General formulations for oil and water-based paints are presented in Table 3 [17].

Table 3. General formulation for oil-based and water-based paint systems

No.	Main raw material category	Oil paint (wt%)	Water paint (wt%)
1	Resin (film former)	20 - 25	30 - 40
2	Additives	0.1 - 2.0	12 - 17
3	Pigments	3.0 - 10	40 - 50
4	Fillers	30 - 40	
5	Solvents	20 - 25	20 - 30

In this study, a solvent-based polyurethane system was formulated using HSU 1908 acrylic polyol resin and Desmodur N75 polyisocyanate at a 1:1 OH/NCO molar ratio. Processed phosphorus slag powder (washed, dried, and ground) was incorporated into the resin matrix at varying slag/resin mass ratios: 0/1, 0.5/1, 0.75/1, 1/1, 1.25/1, and 1.5/1. This methodology aligns with prior research on industrial waste fillers in resin composites [12].

The preparation involved dispersing the slag powder in xylene-diluted HSU 1908 resin via high-speed stirring for 1 hour. Subsequently, the N75 hardener was introduced and stirred for 5 minutes. The mixture was applied to substrates and air-dried to form uniform coatings (~30 µm thickness). Optical opacity and adhesion were evaluated using UV-Vis spectroscopy and a Cross Hatch Adhesion Tester (Elcometer 1542) according to ISO 2409 guidelines (Table 4).

Table 4. Effect of phosphorus slag powder content on paint film adhesion.

No.	Slag powder/resin ratio	Adhesion (score)	Opacity (%)
1	0.0/1	1	95
2	0.5/1	1	96
3	0.75/1	1	97
4	1.00/1	1	98
5	1.25/1	1	99
6	1.50/1	2	99

Results indicate that adhesion and opacity improved as the slag content increased up to 1.25/1. Beyond this threshold (1.5/1), adhesion deteriorated (score 2), likely due to excessive filler causing phase separation or weakened interfacial bonding [15]. The enhanced opacity is attributed to the amorphous Ca-Si particles in the slag, which facilitate effective light scattering [14]. The 1.25/1 slag/resin ratio was determined to be optimal for balancing coverage, adhesion, and economic efficiency, enabling the partial substitution of TiO_2 and other high-cost pigments.

The 1.25/1 coating was further evaluated for steel structure protection. As shown in Table 5, the physicochemical performance indicators strictly comply with the TCVN 8789:2011 standard.

Table 5. Some physicochemical properties of HSU1908/N75/slag powder coating for steel structure protection

No.	Properties	Unit	Determined values	Value according to TCVN 8789:2011	
				Priming	Intermediate coat
1	Dry Content	%	83	≥ 50	≥ 60
2	Fineness	µm	≤ 10	≤ 30	≤ 50
3	Adhesion	score	1	1	1
4	Impact Strength	Kg.cm	90	≥ 45	≥ 45

Additionally, a water-based alkali-resistant primer was formulated using R4322 resin and phosphorus slag at a 1.25/1 ratio. Following neutralization and additive incorporation, the product met the technical specifications of TCVN 8652:2012 (Table 6).

Table 6. Technical Specifications of the Alkali-Resistant Primer

No.	Indicator name	Unit	Test standard	Measured value	Required value
1	Drying Time - Surface dry - Full dry				
		hour	TCVN 2096-1993	0.5	≤ 1[a]
		hour		2	≤ 3[a]
2	Fineness	µm	TCVN 2091:2008	25	≤ 30[a]
3	Adhesion	score	ISO 2409	1	≤ 1[a]
4	Alkali Resistance	hour	TCVN 8635-3:2012	≥ 240	≥ 240[a]
5	Water Resistance	hour	TCVN 8653-3:2012	≥ 480	≥ 480[a]
6	Water Absorption	ml/m^2	TCVN 8652:2012	4	≤ 8[a]
7	Relative Hardness	-	TCVN 8789:2011	0.24	≥ 0.20

Note: "a": required level according to TCVN 8652-2012.

3.2.2 Preparation of HDPE/phosphorus slag composite material

Preliminary investigations successfully used phosphorus slag powder as a reinforcing filler in engineering plastics, including PVC sheets and PE films (Figure 3). Building on its high potential in thermoplastic composites, the material was subsequently applied to produce high-density polyethylene (HDPE) composites for corrugated electrical conduits (Figure 4), consistent with methodologies outlined by Chien et al., [12].

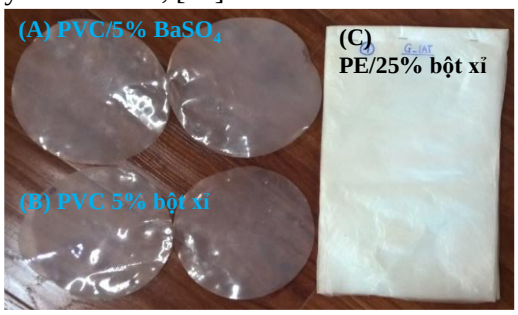


Figure 3. PE films and PVC/slag powder sample.



Figure 4. HDPE/slag powder composite corrugated pipe.

The HDPE/slag composite was prepared via melt-blending in a Haake internal mixer (Germany) at 180 °C for 5 minutes with a rotor speed of 50 rpm. The homogenized melt was hot-pressed using a Toyoseiki hydraulic press (Japan) at 185 °C and 5 MPa for 2 minutes, yielding flat sheets (1.0-1.2 mm thickness). Specimens were air-cooled and conditioned at room temperature for 24 hours prior to mechanical testing.

Test Results: The incorporation of fine phosphorus slag powder (≤ 15 µm) significantly impacted the mechanical performance of the HDPE matrix. As detailed in Table 7, introducing 5 wt% slag notably improved both tensile strength and elongation at break compared to virgin HDPE, indicating effective stress transfer and interfacial bonding. This aligns with Xiao Li et al., who reported enhanced ductility through the high dispersion of fine slag fillers [13].

Elongation at break remained superior to unfilled HDPE across all loading levels, further confirming effective particle dispersion. Conversely, the elastic modulus decreased as filler content increased, reflecting enhanced ductility and flexibility-a trend consistent with Zhang et al. for hybrid Ca-Si-based filler systems [15]. At higher loadings (15-20 wt%), tensile strength declined slightly, likely due to particle agglomeration or matrix discontinuities, as observed by Liu et al. in matrices containing excessive slag or Fe-bearing phases [4]. These formulated materials easily fulfill the performance criteria for corrugated

electrical pipes (TCXDVN 272:2002), offering a sustainable pathway to significantly reduce polymer matrix costs.

Table 7. Mechanical properties of HDPE/phosphorus slag composite material.

No.	Sample	Elastic modulus, (MPa)	Tensile strength, (MPa)	Elongation at break, (%)
1	HDPE	513.34±12.1	28.09±0.8	328.51±15.2
2	HDPE + 5% slag	459.55±10.4	33.86±1.1	469.64±18.4
3	HDPE + 10 % slag	370.48±9.2	28.73±0.9	428.45±14.1
4	HDPE + 15 % slag	337.25±8.5	27.14±0.7	420.12±12.8
5	HDPE + 20 % slag	312.29±7.8	26.93±0.6	339.26±11.5

These results validate phosphorus slag powder as a viable, eco-friendly filler for HDPE composites. The formulated materials meet the performance criteria for corrugated electrical pipes (TCXDVN 272:2002), offering a sustainable pathway to reduce production costs in the plastics industry.

3.2.3 Preparation of wall putty using phosphorus slag powder

Wall putty formulations were developed in strict accordance with the TCVN 7239:2014 standard. Given that mineral fillers typically constitute 55 - 80 wt% of wall putty products thereby governing mechanical strength, workability, and cost the high whiteness, optimal fineness, and chemical stability of the processed slag make it an excellent candidate for full or partial substitution in both exterior and interior applications [7].

A redispersible polyvinyl alcohol (PVA) powder (DA 1120) was used as the polymeric binder to enhance water retention, interfacial adhesion, and overall mechanical strength. Its compatibility with inorganic, modified silicate, and slag-derived fillers has been well-documented in previous literature [2].

Table 8. Formulations of some experimental MTBT samples (10 samples)

Form	**Exterior MTBT**					**Interior MTBT**				
Components	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9	CT10
Black Cement	250	225	200	175	200	-	-	-	-	-
White Cement	-	-	-	-	-	360	324	288	252	200
Slag Powder	715	743	743	743	710	655	691	691	691	715
Lime	0	25	50	75	75	0	36	72	108	70
MK	28	0	0	0	2	36	0	0	0	2
Na_3PO_4	-	-	-	-	5	-	-	-	-	5
DA 1120	7	7	7	7	8	9	9	9	9	8
Total	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**

Following 7 days of curing, two representative samples-CT5 (exterior) and CT10 (interior)-were evaluated for 28-day adhesion strength. CT5 and CT10 achieved 0.814 N/mm² and 0.858 N/mm², respectively, surpassing the TCVN 7239:2014 minimum threshold (> 0.5 N/mm²). The superior performance of the white cement-based formulation (CT10) is likely attributable to enhanced hydration and binder interaction [9].

Table 9. Experimental Results According to TCVN 7239:2014
(*Adhesion and Relative Surface Hardness Calculated After 7 Days*)

Sample, Mixture	Fluidity, (cm)	Setting time (Initial – Final)	Water retention, (%)	Adhesion strength, (N/mm^2)	Relative surface hardness
CT1	10	144-320	97.0	0.24	0.11
CT2	11	200-360	97.5	0.25	0.10
CT3	10.5	320-38	98.5	0.25	0.10
CT4	12	330-450	98.5	0.24	0.09
CT5	11.5	300-400	98.5	0.25	0.13
CT6	10	135-210	96.3	0.24	0.11

CT7	10.5	170-250	97.0	0.25	0.10
CT8	10.5	180-260	97.0	0.24	0.09
CT9	11.5	220-330	98.0	0.24	0.08
CT10	11	200-300	98.0	0.24	0.09

Further performance metrics, including high water retention (>96%), optimal setting times (135-450 min), and acceptable surface hardness (0.08-0.13), corroborate the functional viability of phosphorus slag in MTBT products. These results agree with literature demonstrating that fine Ca-Si particles enhance matrix density and adhesion [13]. Furthermore, the encapsulation of residual phosphorus compounds within the calcium silicate glass matrix mitigates reactivity and environmental leaching risks, ensuring long-term chemical stability [10].

Ultimately, with optimized surface treatment and binder synergy, phosphorus slag-based MTBT formulations offer a highly sustainable and economically advantageous alternative for non-structural construction materials.

3.3. Economic Feasibility and Industrial Scalability Analysis

To evaluate the commercial viability and application prospects of the proposed purification technology, a preliminary techno-economic assessment was performed based on a model processing facility with an annual capacity of 100,000 metric tons of refined slag filler. The analysis considered direct production costs, value addition across target applications, and environmental industrial impact metrics.

Regarding direct unit production costs, raw phosphorus slag is acquired at minimal cost, estimated at \$2.0–\$5.0 per ton, primarily covering regional freight from Tang Loong Industrial Park. The beneficiation operational expenditure (OpEx) encompasses the closed loop hydraulic washing system, chemical precipitation using $Ca(OH)_2$ and PAM dosing, gravity table separation, filtration, drying, and fine mechanical milling to achieve D_{90} <74 μm, collectively incurring an estimated cost of \$20.0–\$25.0 per ton of finished powder. Consequently, the total production cost amounts to approximately \$22.0–\$30.0 per ton of refined functional slag powder.

In terms of economic value addition across target applications, significant cost reductions are achievable in multiple sectors. For polymer matrix applications, commercial HDPE resin costs approximately \$1,100–\$1,300 per ton; substituting 15–20 wt% of the HDPE matrix with refined slag powder (\$30/ton) yields a direct raw material cost reduction of 14.5–18.2% for corrugated pipe manufacturing without compromising mechanical compliance with TCXDVN 272:2002 standards. In protective coatings, high-grade titanium dioxide (TiO_2) pigment and micronized talc command market prices of \$2,800–\$3,200/ton and \$150–\$250/ton, respectively. Incorporating refined slag powder at an optimal ratio of 1.25:1 (slag:resin) achieves 99% opacity and Class 1 adhesion, enabling partial replacement of expensive pigments and fillers and reducing overall paint formulation costs by 18–22%. For construction wall putty applications, standard calcium carbonate filler ($CaCO_3$) costs \$40–\$55/ton, whereas refined slag powder provides equivalent or superior performance with adhesion strength exceeding 0.8 N/mm² compared to the standard requirement of 0.5 N/mm² at a competitive production cost, allowing a 25–30% profit margin enhancement for dry-mix manufacturers.

Regarding environmental and industrial impact, the implementation of this technology converts an environmental hazard currently subject to tipping fees and land accumulation into a high-value commercial asset. For an industrial plant processing 100,000 tons annually, the estimated net annual savings or revenue exceeds \$2.5–\$3.8 million, with an estimated capital investment payback period of 2.6 years. This confirms that the proposed beneficiation strategy is economically lucrative and highly scalable for industrial adoption in circular economy hubs.

4 CONCLUSIONS

This study successfully demonstrates the viability of processed phosphorus slag powder as an aggregate, filler, and reinforcing additive, effectively substituting conventional limestone powder across diverse product categories, including wall putty, solvent- and water-based paints, and high-density polyethylene (HDPE)-based thermoplastics. The findings indicate that properly treated phosphorus slag powder can be incorporated across a broad spectrum of loadings-functioning as either a minor filler or a

major aggregate-while consistently ensuring that the final products comply with stringent national standards, specifically TCVN 7239:2014 for wall putty, TCVN 8789:2011 for protective paints, and TCXDVN 272:2002 for plastic pipes.

Crucially, experimental data across these varied application domains reveal that phosphorus slag powder possesses high inherent compatibility and functionality, completely negating the need for surface modification or complex chemical pretreatments. It can be directly integrated into standard industrial formulations, facilitating the substantial replacement of traditional mineral fillers, such as limestone and talc, thereby significantly reducing both manufacturing costs and the overall environmental footprint.

Amidst the escalating demand for mineral powders and the depletion of virgin resources, the strategic upcycling of industrial by-products like yellow phosphorus slag has emerged as an absolute imperative. Implementing this robust purification approach tangibly supports the transition toward a circular economy, advancing environmental conservation and ensuring sustainable industrial resource management.

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