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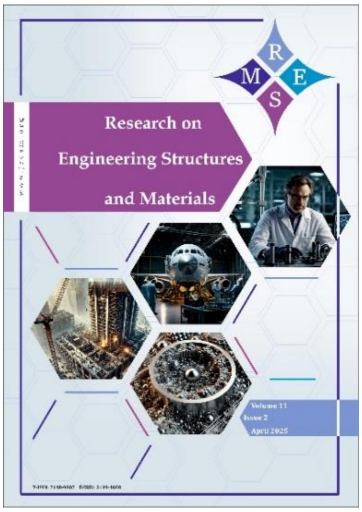

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Research Article

Thermal and mechanical optimization of polyester-based leveling mortars using crushed dune sand

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Abstract

The construction industry in arid regions faces challenges in utilizing locally available dune sand due to its poor gradation and low interparticle friction. This study addresses these limitations by developing a novel leveling mortar composed of thixotropic polyester resin, methyl ethyl ketone peroxide (MEKP) hardener, and crushed dune sand from Taghit, Algeria. The research investigates the synergistic effects of mechanical sand crushing and thermal post-curing (170°C) on the composite's mechanical, thermal, and microstructural properties. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) revealed that crushing transformed rounded dune sand grains into angular particles, enhances surface roughness and interfacial bonding with the resin matrix. Thermal treatment further densified the microstructure, promoting resin cross-linking and reducing organic content, as evidenced by elemental analysis. Mechanical testing demonstrated significant improvements: thermally treated mortars achieved compressive strengths of 116.45–119.9 MPa and flexural strengths of 38.75–45.25 MPa, representing a 10–12% and 89–98% increase over untreated counterparts, respectively. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) confirmed the composite's thermal stability up to 410°C, with decomposition pathways dominated by resin pyrolysis. The findings highlight the valorization of dune sand as a sustainable alternative to conventional aggregates, reducing environmental impact and transportation costs. This work advances the understanding of resin-filler interactions in polymer composites, offering a scalable solution for high-performance, eco-friendly construction materials in resource-constrained arid regions.

1. Introduction

The construction industry continually seeks innovative materials that combine durability, cost-effectiveness, and environmental sustainability [1]. Among these materials, polymer-based composites—including leveling mortars—have garnered significant attention due to their adaptability, mechanical resilience, and potential to incorporate locally sourced aggregates [2,3]. Leveling mortar is a specialized construction material used to create smooth, flat surfaces on floors, walls, or substrates before applying final finishes such as tiles, epoxy coatings, or pavers. Unlike traditional cement-based mortars, polymer-modified leveling mortars offer superior workability, faster curing times, and enhanced bonding strength, making them ideal for both structural and non-structural applications in modern construction.

In arid regions, dune sand represents an abundant yet underutilized resource, often dismissed in traditional construction due to its fine granulometry and rounded particle morphology [4,5]. However, recent advancements in composite technology have demonstrated that such sands can

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be transformed into viable building materials when combined with polymeric binders, offering a sustainable alternative to conventional aggregates [6-8]. This study explores the development and characterization of a novel thixotropic polyester resin-based leveling mortar composed of methyl ethyl ketone peroxide (MEKP) hardener and crushed dune sand sourced from Taghit, Algeria. By integrating mechanical, thermal, and microstructural analyses, this research elucidates how material processing—particularly crushing and thermal treatment—enhances the performance of dune sand-based composites, paving the way for their broader application in construction.

The utilization of dune sand in construction has historically been limited by its poor gradation and low interparticle friction, which hinder compaction and mechanical stability [9-11]. Unlike river or crushed sands, dune sand grains are shaped by prolonged aeolian transport [12,13], resulting in smooth, spherical particles that reduce interlocking and adhesion in cementitious matrices. However, mechanical crushing has emerged as a promising method to modify sand morphology, creating angular particles with enhanced surface roughness and specific surface area [14,15]. These attributes improve particle-matrix bonding in composites, a critical factor for load-bearing applications. Recent studies have shown that crushed dune sand, when combined with organic binders like polyester resins, can yield mortars with superior mechanical properties compared to untreated counterparts [16]. This approach not only valorizes a readily available natural resource but also reduces reliance on energy-intensive conventional aggregates [17,18].

Thixotropic polyester resins, a class of unsaturated polymers, are particularly suited for composite formulations due to their unique rheological behavior [19]. Under shear stress, their viscosity decreases, enabling easy mixing and application, while stability at rest prevents sagging or segregation [20]. When catalyzed by MEKP hardeners, these resins undergo rapid polymerization, forming a rigid matrix that encapsulates filler materials. The chemical structure of polyester resins—comprising polyhydric alcohols and dibasic acids—facilitates cross-linking, which enhances mechanical strength and thermal resistance [21]. However, the interfacial compatibility between resin and filler remains a critical challenge, as weak bonding can lead to premature failure under stress. To address this, researchers have investigated post-curing treatments, such as thermal exposure, to further densify the matrix and strengthen the resin-filler interface. Such treatments promote additional cross-linking and microstructural refinement, which are pivotal for optimizing composite performance [22-24].

In this study, the synergistic effects of crushed dune sand and thermal post-curing on the properties of polyester-based leveling mortar are systematically investigated. The crushed sand, characterized by its angular morphology and high silica content (>95%), serves as both a filler and reinforcement agent [25]. Its interaction with the resin matrix is analyzed through scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), which reveal morphological and chemical changes induced by mechanical processing and heat treatment [26]. Differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TGA) provide insights into the thermal stability and decomposition pathways of the composite [27,28], while mechanical testing quantifies improvements in compressive and flexural strength [29].

The motivation for this work stems from two key gaps in existing literature. First, while several studies have explored the use of dune sand in concrete, limited attention has been paid to its application in polymer-based mortars, particularly those subjected to thermal modification. Second, the interfacial mechanisms between crushed sand and polyester resins remain poorly understood, especially in the context of post-curing treatments. By addressing these gaps, this research contributes to the development of high-performance, sustainable construction materials tailored for arid environments.

The findings of this study hold significant practical implications. For instance, the enhanced mechanical properties of heat-treated leveling mortars could expand their use in load-bearing structures, flooring systems, or repair applications where traditional materials falter. Additionally, the use of locally sourced dune sand reduces transportation costs and environmental impact, aligning with global trends toward circular economy practices. From a scientific perspective, this work advances the understanding of resin-filler interactions in composites, offering a framework for optimizing material formulations through controlled processing techniques.

2. Materials and Methods

2.1. Materials

The materials used in this study include thixotropic polyester resin, Butanox M50 resin hardener and dune sand sourced from Taghit (Algeria), which is well classified with indice of classification lower than 2.5 [10]. Thixotropic polyester resin is a type of unsaturated polyester resin with a viscosity that decreases under shear stress, making it easy to mix and apply while maintaining stability at rest [19]. It is commonly formulated from polyhydric alcohols and dibasic organic acids, with the general chemical formula $(C_2H_4O)n(C_8H_6O_4)m$. The Butanox M50 hardener is a methyl ethyl ketone peroxide (MEKP), which serves as a catalyst in the polymerization process of polyester resins [30,31]. Its chemical formula is $C_8H_{18}O_6$, and it ensures proper curing and hardening of the resin matrix. The crushed dune sand primarily consists of silicon dioxide (SiO_2) and is used as a filler material to improve the mechanical properties of the leveling mortar, offering strength and durability.

Particle Size Distribution (PSD) curve of crushed dune sand in The Fig. 1 shows a well-graded material with a mix of fine, medium, and coarse particles, ensuring good compaction and stability. The curve follows a smooth progression from 0% to 100% cumulative passing, indicating a broad range of particle sizes suitable for polymer- leveling mortar s. From a chemical perspective Table 1, it is important to note that this sand has a remarkably high silica content, consisting of fine quartz grains. Its silica concentration exceeds 95%, classifying it as siliceous sand [10,11].

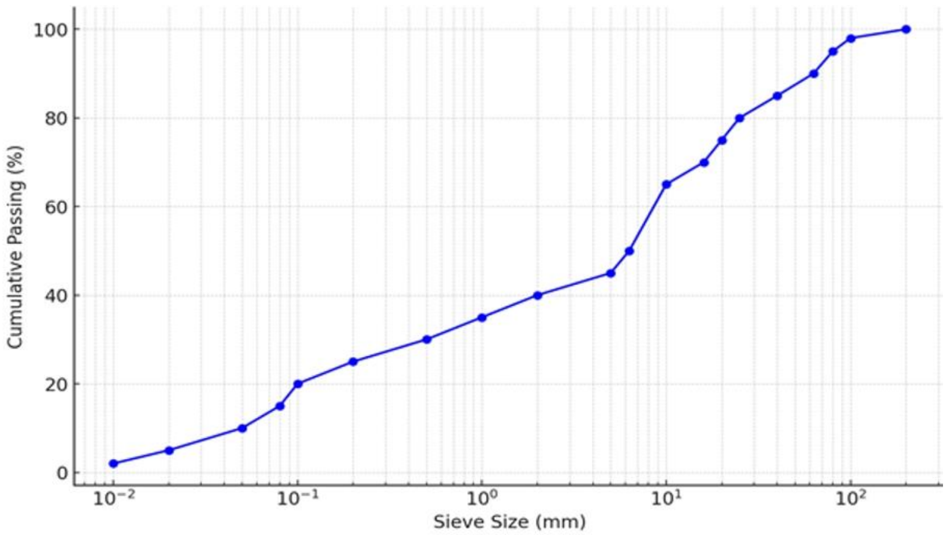


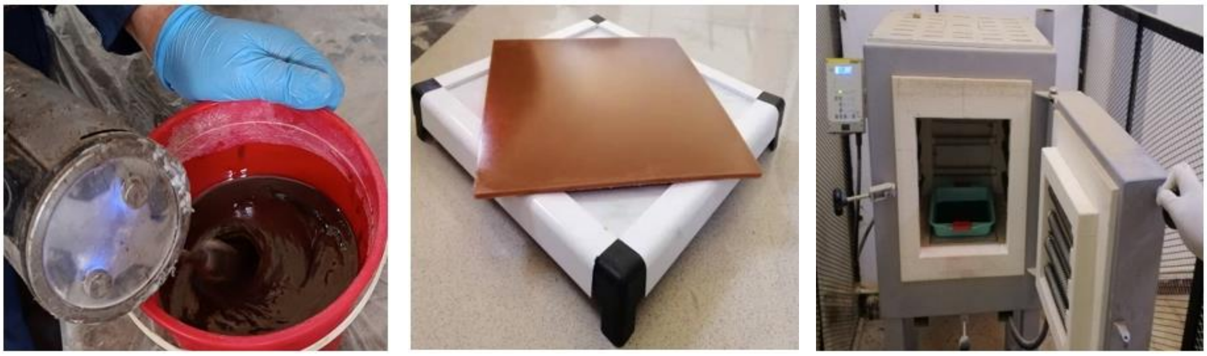
Fig. 1. Particle size distribution curve of Crushed dune sand

Table 1. Crushed dune sand chemical compositions

Composition (%)	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2O	K2O	Other	LOI
Crushed dune sand	97.15	0.79	0.21	0.11	0.05	0.14	0.18	0.02	< 0.02	0.58

The preparation of the leveling mortar mixture follows a well-defined and systematic procedure. Initially, polyester resin is added to the crushed dune sand and mixed thoroughly to ensure a homogeneous distribution of the resin throughout the granular matrix. Following this, the hardening agent Butanox M50 is carefully introduced into the blend, initiating the polymerization reaction. The curing time of the mixture typically ranges between 40 to 80 seconds, depending on the quantity and proportions of the individual components used in the formulation. Once the mixture reaches the appropriate consistency, it is poured into predefined molds for shaping. To ensure uniform compaction and to eliminate entrapped air that could compromise the structural integrity, the molds are subjected to a controlled vibration process.

After molding, the samples are left to cure under ambient controlled conditions, allowing for complete polymerization of the resin matrix. In our research, a series of samples also underwent thermal post-treatment to investigate their behavior under elevated temperatures. Specifically, the leveling mortar was gradually heated to 90°C over a period of 20 minutes, then further elevated to 170°C within 50 minutes. This peak temperature was maintained for a specified duration to allow for thermal interaction within the material. Following this, the specimens were cooled in a controlled manner, returning to room temperature over the course of 170 minutes. This thermal treatment protocol enabled us to closely examine the physical and chemical transformations occurring within the mortar, especially with regard to dehydration processes, improvements in thermal stability, and enhancements in mechanical performance following exposure to heat. As shown in Fig. 2, the heat-treated samples demonstrated noticeable changes that provide valuable insights into the mortar's structural behavior under thermal stress.



(a) (b) (c)

Fig. 2. Preparation of samples (a) Leveling mortar preparation, (b) leveling mortar, (c) Heat the leveling mortar

Through the Table 2, The mortar mix comprises 55-65% crushed dune sand (primary filler), 30-40% polyester resin (binding agent), and a small 0.15-0.25% hardener (curing agent) by weight. Sand dominates the mix, followed by resin, with hardener used minimally.

Table 2. Composition ranges of mortar constituents by weight

Mortar constituents	Range (% by weight)
Thixotropic polyester resin	30-40
Crushed dune sand	55-65
Hardener	0.15-0.25

2.2. Methods

In our study, we conducted a series of experimental analyses to evaluate the thermal behavior, microstructure, and stability of different composite materials composed of polyester resin and sand derivatives. Our experiments focused on four sample types: dune sand (DS), crushed dune sand (CDS), leveling mortar (M), and heat-treated leveling mortar (TM), as depicted in Fig. 3.

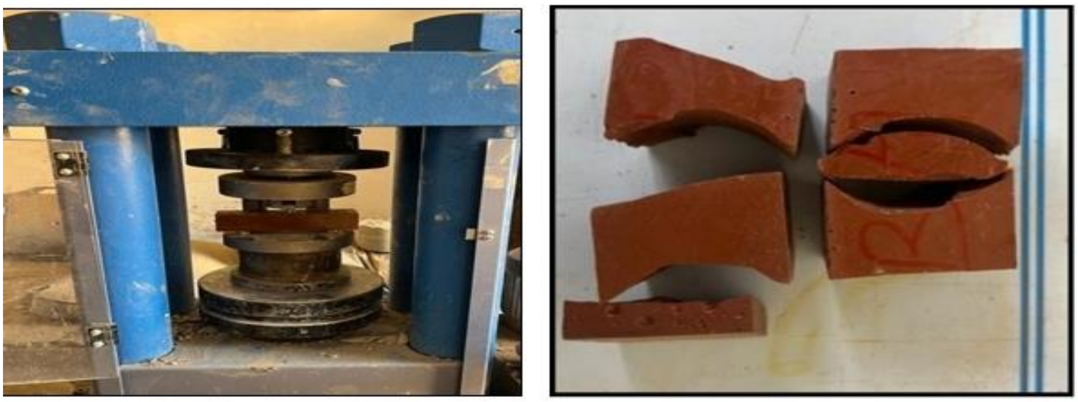
To assess thermal properties, we employed Differential Scanning Calorimetry (DSC), Differential Thermal Analysis (DTA), and Thermogravimetric Analysis (TGA) using a TA Instruments Q600. We carried out the tests under an inert nitrogen (N_2) atmosphere with a controlled heating rate of 20°C/min, spanning a broad temperature range from 40.91°C to 1190.41°C. Prior to testing, all samples were oven-dried at 105°C for 24 hours to remove moisture, and their granulometry was analyzed to ensure a particle size below 100 µm.

Additionally, we used a Scanning Electron Microscope (SEM) to observe the morphological and microstructural changes in the samples before and after crushing and thermal treatment. We also used Energy Dispersive X-ray Spectroscopy (EDS) coupled with SEM to determine the elemental compositions of the samples, tracking how heat exposure influenced the chemical makeup, particularly the degradation of organic resin and the increased visibility of mineral phases. We studied both untreated and thermally treated leveling mortar s to compare mechanical strength and thermal stability, emphasizing the role of heat in polymer cross-linking and microstructural reinforcement.

(a) (b) (c) (d)

Fig. 3. Samples (a) dune sand, (b) crushed dune sand, (c) leveling mortar and (d) treated leveling mortar

(a)



(b)

Fig. 3. Mechanical test (a) compression and (b) flexural of leveling mortars

The compression tests were performed in accordance with the NF EN 772-1 standard. Test specimens had prismatic dimensions of 40 × 40 × 160 mm^3, which is a typical size for mortar testing. The tests were carried out on a hydraulic press with a maximum load capacity of 300 kN, ensuring a controlled and uniform application of axial load until specimen failure. The loading rate was set to a constant and slow displacement speed of 0.5 N/s applied via the upper platen. Regarding flexural strength, we used the three-point bending test method, according to NF EN 12390-5 standard. The same 40 × 40 × 160 mm^3 specimens were used, with the support span fixed at 100 mm. The loading rate was precisely set to 0.05 kN/s, a relatively slow rate that minimizes vibrations or impact loads that could distort the mechanical response. These tests were conducted using a PILOT COMPACT-Line testing machine.

In this study, we selected the number of samples for each type of analysis to ensure both reliability and reproducibility of the results. For the mechanical testing, I prepared a total of twelve prismatic specimens (40 × 40 × 160 mm^3), divided equally between untreated and heat-treated mortars—three specimens for flexural testing and three for compressive strength per mortar type, respectively. Regarding the thermal analyses, including Differential Scanning Calorimetry (DSC), Differential Thermal Analysis (DTA), and Thermogravimetric Analysis (TGA), I used four distinct sample types: natural dune sand (DS), crushed dune sand (CDS), untreated mortar (M), and heat-treated mortar (TM). For each thermal technique, I tested one sample per material type, amounting to twelve thermal samples in total (4 materials × 3 techniques). Finally, for the microstructural analysis, I performed Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) on four representative samples—DS, CDS, M, and TM—using one specimen per type to capture the morphological and compositional differences introduced by crushing and thermal treatment. Although the sample size (n = 3 per condition) is limited, it aligns with standard preliminary mechanical testing practices for mortar formulations. This study aims to establish foundational insights; future work will include larger sample sets to strengthen statistical power.

3. Results and Discussion

3.1. SEM-EDS Analysis

The dune sand (DS) exhibits a well-rounded and smooth morphology, characteristic of prolonged aeolian transport and weathering processes. These rounded grains provide high fluidity and lower interparticle friction, which influences their behavior in construction applications. However, after the mechanical crushing process, the resulting Crushed Dune Sand (CDS) undergoes significant morphological transformations. The SEM images in Fig. 4 reveal that the grains become angular, fractured, and highly irregular in shape. The smooth surfaces of the natural dune sand are replaced by sharp edges and increased surface roughness, which significantly enhances the specific surface area of the particles.

This change in microstructure directly impacts the physical properties of the sand. The increased angularity leads to better interlocking between particles, which improves the mechanical performance of leveling mortar and concrete formulations. Additionally, the fractured nature of the grains enhances their adhesion capacity when mixed with binding agents such as cement or resin. However, the rough and jagged texture also means that crushed dune sand may require a higher water or binder content in composite materials to maintain workability. This increase in specific surface area can be advantageous in applications requiring enhanced cohesion and compactness in leveling mortar s and concretes. As seen in Fig. 4, the treated leveling mortar surface shows evidence of a reconfigured matrix, where the initially discrete sand-resin interfaces in the uncured leveling mortar (M) evolve into a more complex, interlocking morphology. While some microcracks and fractures are indeed visible, their distribution appears controlled and may reflect a densification process rather than simple structural failure.

The observed microstructural changes can be interpreted as thermal post-curing effects, where elevated temperatures induce further cross-linking within the polymeric resin matrix. This post-curing process leads to increased stiffness and a more rigid bond at the resin–sand interface. Instead of acting purely as a point of mechanical weakness, the interface transitions into a zone of constrained deformation, which may enhance stress transfer between components and improve the composite's load-bearing capabilities. Additionally, the roughened and more textured surfaces of the sand grains in TM, compared to the smoother matrix in M, suggest enhanced mechanical interlocking. Such morphological features can strengthen particle–matrix adhesion, especially under compressive and shear loads, contributing positively to the overall performance of the leveling mortar. Moreover, the apparent presence of thermally fused resin domains in TM implies a partial redistribution of the binder material, which could fill previously undetected micro voids or reinforce interparticle bridges.

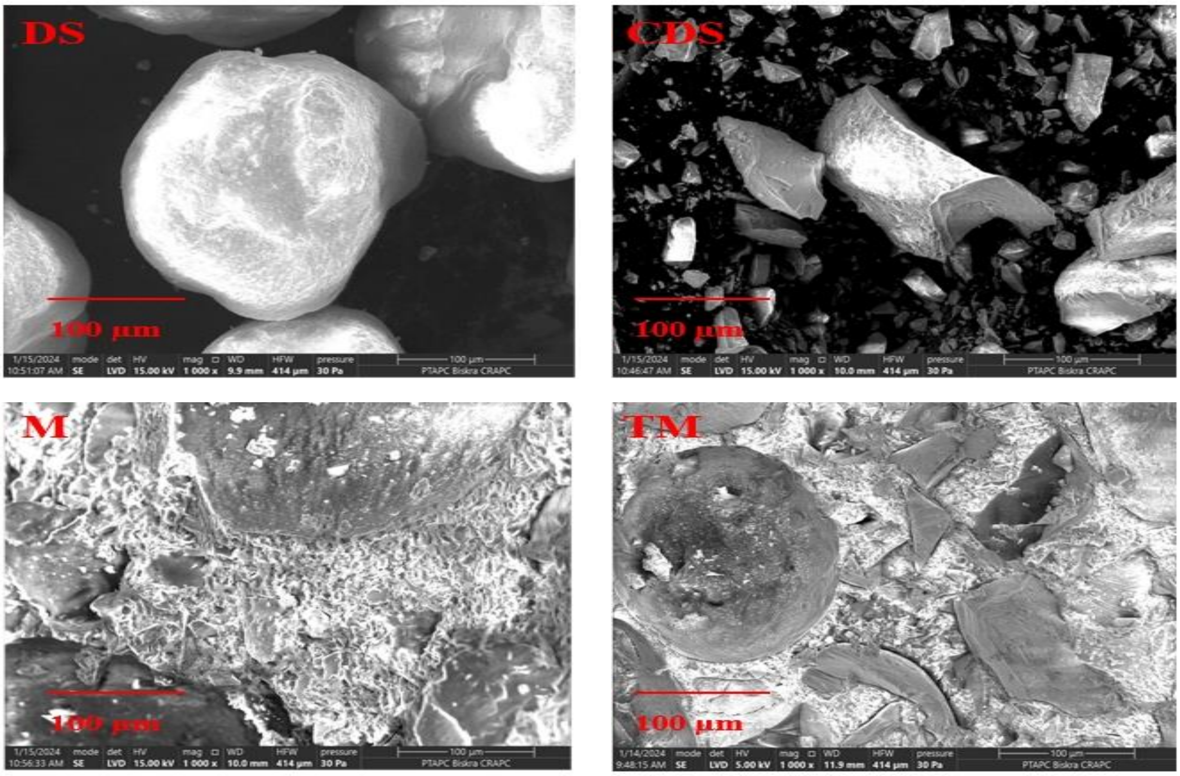
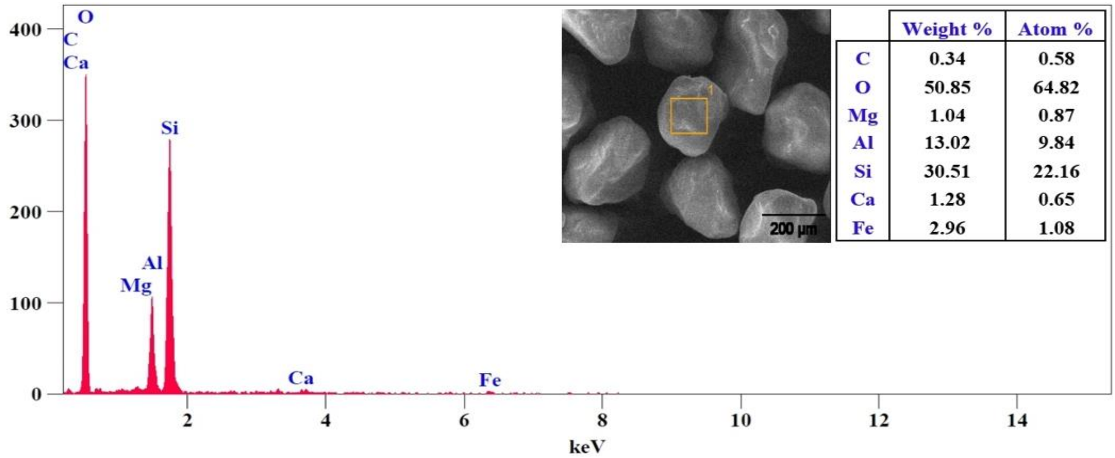


Fig. 4. SEM micrographs of dune sand (DS), Crushed Dune Sand (CDS), leveling mortar (M), treated leveling mortar (TM)

The Energy Dispersive X-ray Spectroscopy (EDS) analysis presented in Fig. 5 offers a detailed comparison between dune sand (DS) and mechanically processed crushed dune sand (CDS), providing insight into how morphological and chemical changes impact material behavior especially when cross-referenced with Scanning Electron Microscopy (SEM) observations from Fig. 4 and the associated analysis in section 3.1.For dune sand (DS) (Fig. 5a), the EDS spectrum and the corresponding quantitative results indicate that the dominant elements are oxygen (50.85 wt%), silicon (30.51 wt%), and aluminum (13.02 wt%), with smaller contributions from calcium (1.28 wt%), magnesium (1.04 wt%), and iron (2.96 wt%). This composition is typical of silicate-rich sands, particularly those dominated by quartz (SiO_2) and aluminosilicates, such as feldspar and clay minerals. The relatively low carbon content (0.34 wt%) suggests a minimal presence of organic or carbonate material in the natural dune sand.

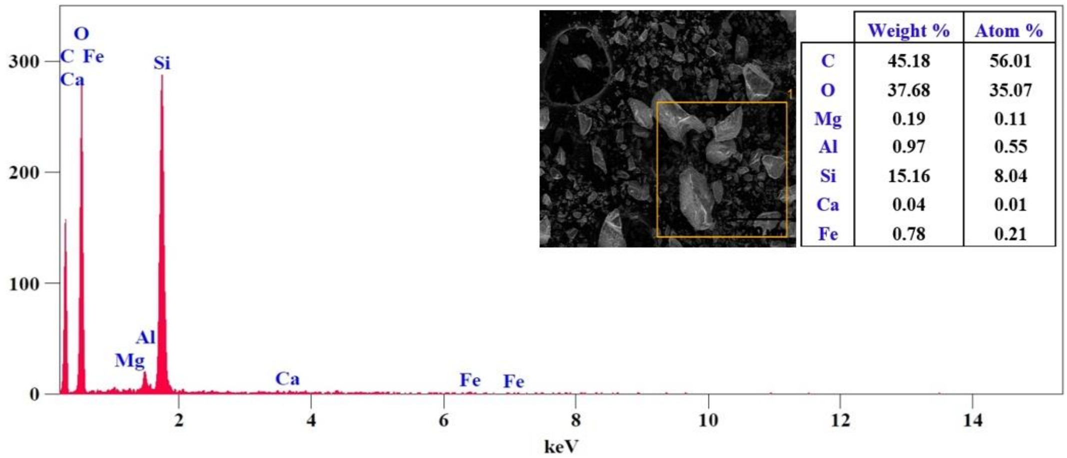
In contrast, crushed dune sand (CDS) (Fig. 5b) displays a dramatically different elemental profile. The most striking feature is the sharp increase in carbon content (45.18 wt%), accompanied by a notable decrease in oxygen (37.68 wt%), silicon (15.16 wt%), and aluminum (0.97 wt%). These changes imply a significant transformation in surface chemistry following mechanical crushing. The elevated carbon may originate from surface contamination, adsorption of airborne organic materials, or testing environments. The decreased silicon and aluminum contents suggest partial masking of silicate phases or loss due to dust or fragmentation during crushing. Iron and calcium are present in trace amounts in both sand types but appear reduced in CDS.

In the leveling mortar (Fig. 6a), the EDS spectrum indicates a dominant presence of carbon (60.36 wt %) and oxygen (31.56 wt %), which together constitute over 90% of the sample by weight. This is consistent with the presence of organic polymeric resins or binders used in the leveling mortar matrix. The relatively low silicon content (7.39 wt %) reflects the limited exposure of sand particles on the surface, suggesting that they are mostly embedded within the binder. Minor traces of calcium (0.56 wt %) and iron (0.13 wt %) are also observed.



	Weight %	Atom %
C	0.34	0.58
O	50.85	64.82
Mg	1.04	0.87
Al	13.02	9.84
Si	30.51	22.16
Ca	1.28	0.65
Fe	2.96	1.08

(a)



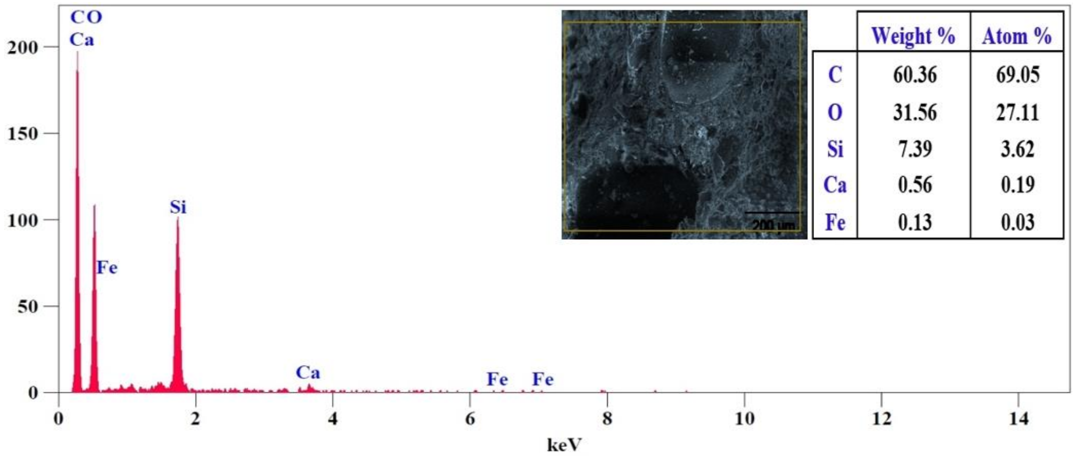
	Weight %	Atom %
C	45.18	56.01
O	37.68	35.07
Mg	0.19	0.11
Al	0.97	0.55
Si	15.16	8.04
Ca	0.04	0.01
Fe	0.78	0.21

(b)

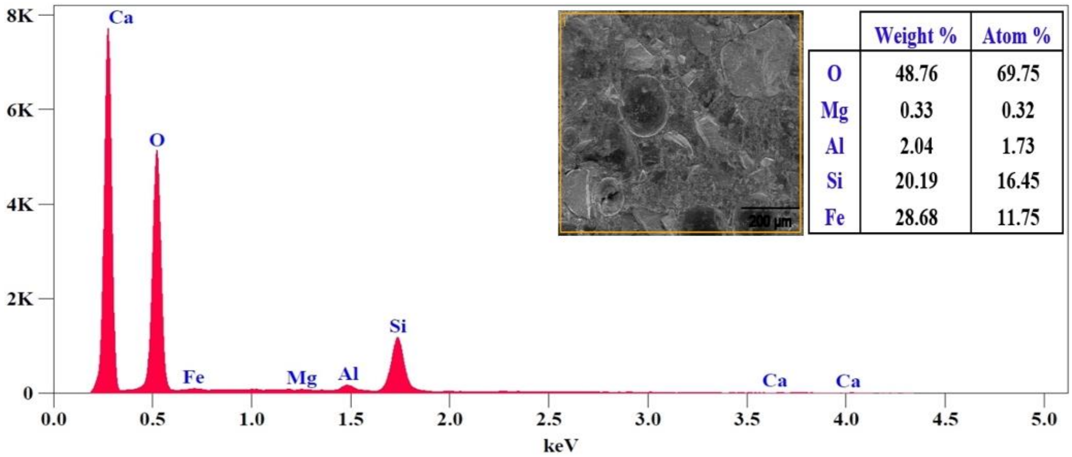
Fig. 5. SEM-EDS test results of (a) Dune sand and (b)Crushed Dune Sand

Following thermal treatment, the composition of the treated leveling mortar (TM) (Fig. 6b) shifts markedly. Carbon is no longer the dominant element; instead, oxygen content rises significantly to 48.76 wt %, followed by iron (28.68 wt %), silicon (20.19 wt %), and aluminum (2.04 wt %), while carbon is no longer listed, due to degradation, volatilization, or coverage loss of organic components during heating. This shift in elemental profile reflects the decomposition or redistribution of the polymeric resin and increased surface exposure of the mineral aggregates (primarily silicates and oxides). These EDS findings are in strong agreement with the SEM observations discussed in Fig. 4 and section 3.1. Initially, the leveling mortar (M) features a smooth and continuous matrix, with discrete sand-resin interfaces. This structure, rich in organic carbon, appears homogeneous but contains potential weak points due to poor interfacial bonding.

Upon thermal treatment, SEM images reveal that the resin undergoes post-curing and densification, transforming the matrix into a more complex, interlocking morphology. The sand grains become more exposed, and the interface becomes mechanically and chemically more integrated. This is visually supported by the emergence of rough, textured surfaces in the SEM micrographs of TM, indicating better particle–matrix adhesion. Additionally, the higher presence of Fe, Al, and Si detected by EDS in TM suggests that inorganic fillers and natural sand components are more prominently involved in the structural skeleton of the treated leveling mortar. The dramatic drop in carbon percentage and rise in metallic and silicate components in TM highlights the thermally induced transformation of the leveling mortar from an organic-dominant to a mineral-dominant composite. This transition implies enhanced mechanical performance, thermal resistance, and structural integrity.



(a)



(b)

Fig. 6. SEM-EDS test results of (a) Leveling mortar (M) and (b) Treated Leveling mortar (TM)

Table 3. Elemental composition found in EDX analysis of dune sand (DS), Crushed Dune Sand (CDS), mortar (M), treated mortar (TM).

	DS	CDS	M	TM
Element	C	C	C	O
	O	O	O	Mg
	Mg	Mg	Si	Al
	Al	Al	Ca	Si
	Si	Si	Fe	Fe
	Ca	Ca	-	-
	Fe	Fe	-	-
Weight %	0.34	45.18	60.36	48.76
	50.85	37.68	31.56	0.33
	1.04	0.19	7.39	2.04
	13.02	0.97	0.56	20.19
	30.51	15.16	0.13	28.68
	1.28	0.04	-	-
	2.96	0.78	-	-
Total	100	100	100	100

Atom %	0.58	56.01	69.05	69.75
	64.82	35.07	27.11	0.32
	0.87	0.11	3.62	1.73
	9.84	0.55	0.19	16.45
	22.16	8.04	0.03	11.75
	0.65	0.01	-	-
	1.08	0.21	-	-
Total	100	100	100	100

3.2. Strength of Leveling Mortars

In Figure 7, the leveling mortar mixtures without heat treatment show moderate flexural and high compressive strength values. Leveling mortar made with dune sand (DS) exhibits a compressive strength of 104.2 MPa and a flexural strength of 20.5 MPa. In contrast, leveling mortar made with crushed dune sand (CDS) demonstrates slightly better performance, with a compressive strength of 109.85 MPa and a flexural strength of 22.8 MPa. This marginal improvement in strength for the CDS-based leveling mortar is attributable to the angular and rough texture of crushed sand particles, as highlighted in the SEM analysis (Figure 4).

The improved particle interlocking in CDS enhances the mechanical engagement between the sand and binder matrix, especially under compressive loads. However, due to the presence of significant organic matrix (as shown in the EDS of Leveling mortar M, Figure 6a), the bonding remains limited, and flexural resistance is relatively low in both types. Following thermal treatment, Figure 8 reveals a substantial increase in both flexural and compressive strength for both leveling mortar types. Leveling mortar (DS) after heat treatment reaches a compressive strength of 116.45 MPa and a flexural strength of 38.75 MPa—almost doubling its flexural strength compared to the untreated version. The CDS-based leveling mortar shows even more significant gains, with compressive strength climbing to 119.9 MPa and flexural strength to 45.25 MPa. These improvements are well-supported by the EDS results in Figure 6b, where a clear increase in elemental components associated with sand (Si, Fe, Al) is evident, and carbon content diminishes. This indicates partial decomposition of the organic binder and better exposure of mineral particles, leading to a denser, more cohesive structure. SEM observations (Figure 4) also confirm matrix densification, interfacial interlocking, and resin reconfiguration after thermal treatment, which directly contribute to the improved mechanical behavior. When comparing both figures, the impact of thermal treatment is profound, particularly on flexural strength, which nearly doubles for both DS and CDS leveling mortar s. While compressive strength improves by approximately 10–12%, the increase in flexural resistance is much more significant—from 20.5 MPa to 38.75 MPa in DS leveling mortar s and 22.8 MPa to 45.25 MPa in CDS leveling mortar s. This highlights the role of thermal curing in enhancing the toughness and ductility of the leveling mortar, not just its strength under static load.

The increase in flexural strength following heat treatment was statistically significant for both DS ($p = 0.01$) and CDS mortars ($p = 0.008$). Similarly, compressive strength improvements were statistically significant ($p < 0.05$). The strength differences between mortars made with crushed and uncrushed dune sand were also statistically significant for both flexural and compressive tests ($p < 0.05$) This leveling mortar characterized by several noteworthy chemical properties, primarily derived from its constituents—crushed dune sand and thixotropic polyester resin. The crushed dune sand, mainly composed of quartz (SiO_2), also includes traces of feldspar and mica, and exhibits a fine granulometry that enhances surface reactivity. Upon incorporation with the polyester resin, a polymer derived from unsaturated acids like maleic acid and glycols such as propylene glycol, a strong chemical bond forms through cross-linking when a hardener is added. This polymerization process results in a thermoset matrix with improved chemical resistance, reduced water permeability, and increased structural integrity.

Table 4. Strength of the leveling mortar without heat treatment

Tests	DS (mean ± SD)	CDS (mean ± SD)
Flexion (MPa)	20.5 ± 1.1	20.5 ± 1.1
Compression (MPa)	104.2 ± 2.2	104.2 ± 2.2
Modulus of Elasticity (E) (MPa)	10.2 ± 0.3	10.2 ± 0.3
Poisson's Ratio (ν)	0.21 ± 0.02	0.21 ± 0.02

Table 5. Strength of the leveling mortar after heat treatment

Tests	DS (mean ± SD)	CDS (mean ± SD)
Flexion (MPa)	38.75± 1.1	45.25± 1.1
Compression (MPa)	116.45± 2.2	119.9± 2.2
Modulus of Elasticity (E) (MPa)	10.8± 0.3	10.94± 0.3
Poisson's Ratio (ν)	0.19± 0.02	0.18± 0.02

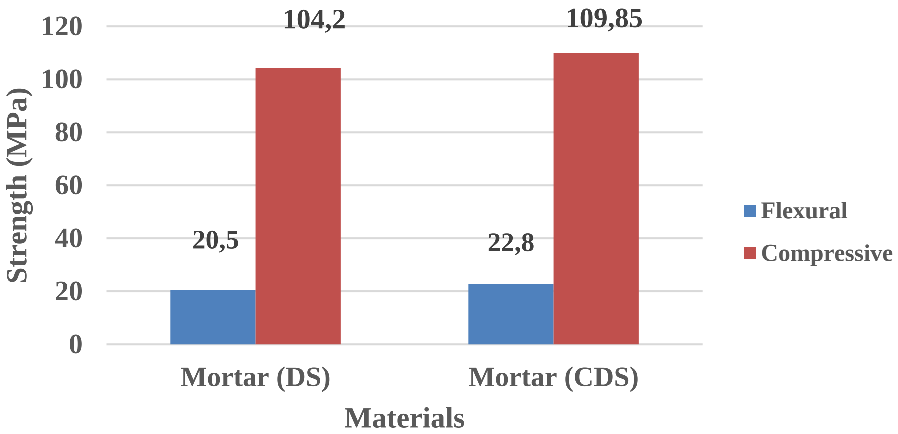


Fig. 7. Strength of leveling mortar without heat treatment

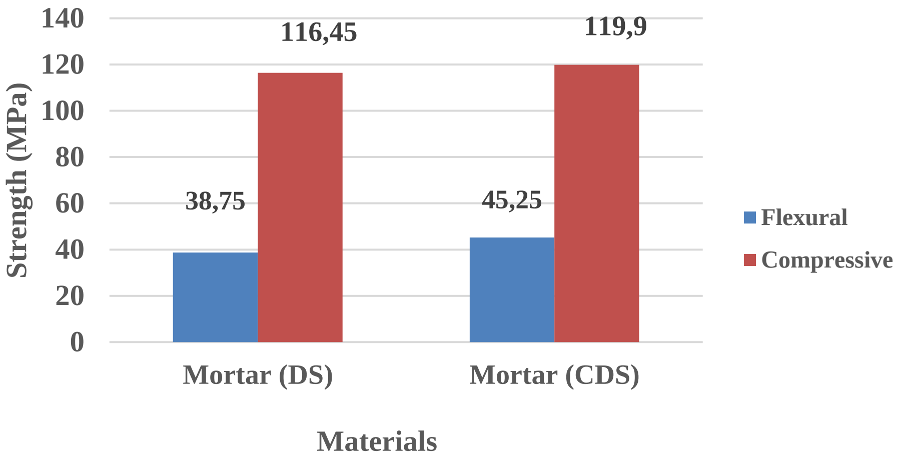


Fig. 8. Strength of treated leveling mortar

3.3. Thermal Analysis

3.3.1 Differential Scanning Calorimetry (DSC)

In the Fig. 9, The Differential Scanning Calorimetry (DSC) curve analysis for the leveling mortar and treated leveling mortar under varying temperatures. Which consists of crushed dune sand and thixotropic polyester resin, along with the dune sand and crushed dune sand, provides valuable insights into the thermal properties and behavior of these materials.

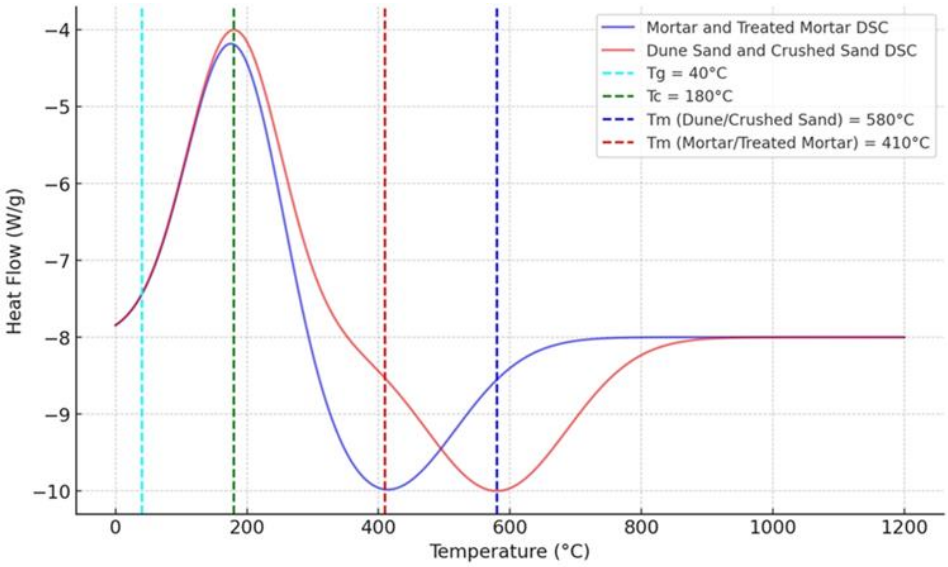


Fig. 9. Differential scanning calorimetry (DSC) curve of dune sand, crushed dune sand, leveling mortar and treated leveling mortar

The first transition, at 40°C, represents the glass transition temperature (Tg) of the polyester resin. This transition is indicative of the shift from a rigid, glassy state to a rubberier state, suggesting that the material experiences increased segmental mobility beyond this temperature. The relatively low Tg is characteristic of polyester resins used in leveling mortar s, confirming their flexibility and adhesion properties at lower temperatures.

A crystallization peak (Tc ≈ 180°C) suggests an exothermic process, it is associated with the rearrangement of the polyester resin polymer chains. Given that the heat-treated leveling mortar was subjected to temperatures up to 170°C, this indicates that partial crystallization may have already occurred before testing. This prior heat exposure could have influenced the polymer structure, making it more stable compared to untreated leveling mortar. The thermal event observed at ~410°C corresponds to the onset of thermal decomposition temperature of the polyester resin matrix. While this is often exothermic in oxidative environments, under the inert nitrogen atmosphere used in DSC, the process may appear as a weakly endothermic transition due to bond cleavage within the polymer chains.

$$(C_2H_4O)n(C_8H_6O_4)m \rightarrow CO_2 + CO + H_2O + C_6H_4(CO)_2O + C_xH_y + \text{residual carbon} \quad (1)$$

In the DSC curves, the endothermic peak observed around 573°C corresponds to the well-documented α-quartz to β-quartz phase transition of silica (SiO_2), which is a reversible solid-state transformation and not a melting event. This transition involves a structural rearrangement in the quartz lattice without material liquefaction. It is important to note that quartz melts at a significantly higher temperature, approximately 1650°C. Therefore, the thermal effect observed at ~573°C reflects the polymorphic transformation of the quartz phase present in the sand aggregates, which can influence the composite's thermal response but does not indicate the melting of mineral components.

3.3.2 Differential Thermal Analysis (DTA)

The Differential Thermal Analysis (DTA) curve of dune sand and crushed dune sand in the Fig. 10 reveals key thermal events related to the decomposition and transformation of its mineral components. The first noticeable feature is an endothermic reaction occurring between 400°C and 600°C, which is attributed to the dehydration of clay minerals and the α-quartz to β-quartz phase transition. This reaction involves the loss of bound water from minerals such as kaolinite, which decomposes into metakaolin and releases water vapor. Additionally, the quartz polymorphic transition at around 573°C further contributes to this endothermic behavior, as quartz undergoes structural rearrangement, which absorbs heat. These transformations indicate the progressive thermal decomposition of the sand's mineral phases.

$$Al_2Si_2O_5(OH)_4 \rightarrow Al_2Si_2O_7 + 2H_2O \tag{3}$$

The second major feature in the DTA curve is an exothermic reaction occurring between 800°C and 1000°C, corresponding to the crystallization and phase transformation of silica-based compounds. This reaction is associated with the reorganization of amorphous silica (SiO_2) into stable crystalline phases such as cristobalite or tridymite, releasing energy in the process. If organic impurities are present, their oxidation may also contribute to this exothermic peak. The similarity in thermal events between dune sand and crushed dune sand suggests that crushing does not significantly alter the thermal stability of the material, though it may slightly affect reaction intensities due to increased surface area and reactivity.

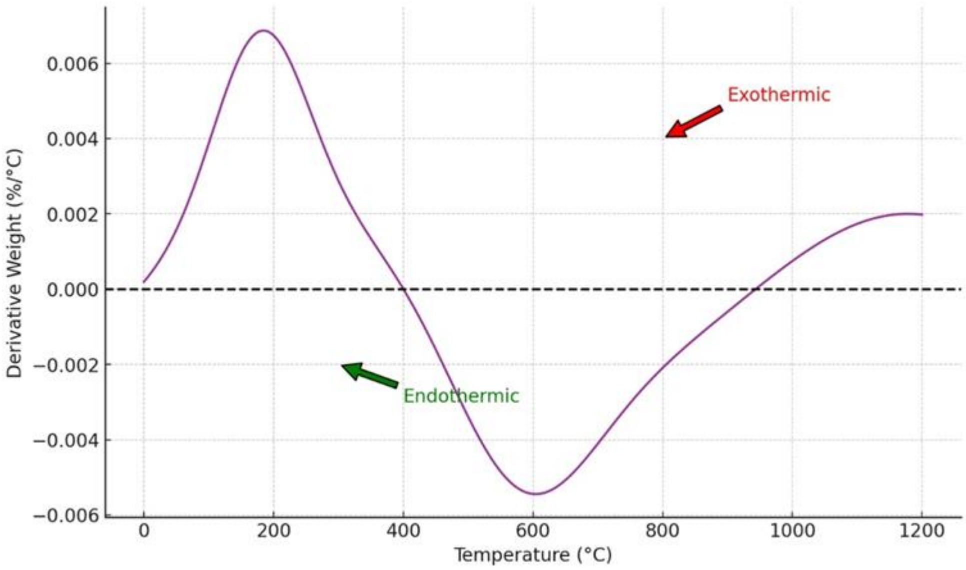


Fig. 10. Differential Thermal Analysis (DTA) curve of dune sand and crushed dune sand

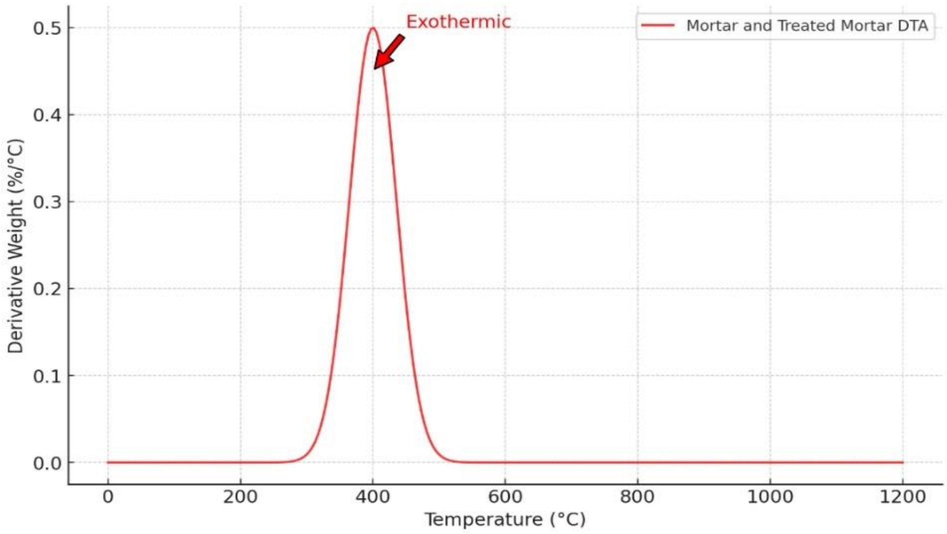


Fig. 11. Differential Thermal Analysis (DTA) curve of leveling mortar and treated leveling mortar

Analyzing the DTA curve of both leveling mortar and treated leveling mortar sheds light on their thermal properties, emphasizing phase changes and decomposition processes (Fig. 11). The pronounced thermal event around 410°C is associated with the degradation of the polyester resin.

While recorded as exothermic in DTA—possibly due to minor oxidative effects or further cross-linking reactions—the same process may appear differently in DSC, which operates under strictly inert conditions. Beyond this exothermic peak, the curve stabilizes, suggesting that no significant thermal events occur at higher temperatures. This indicates that once the polyester resin decomposes, the remaining inorganic components of the leveling mortar, primarily silica (SiO_2) and calcium-based compounds, exhibit thermal stability up to 1200°C. The fact that both leveling mortar and heat-treated leveling mortar exhibit similar exothermic behavior at the same temperature suggests that the heat treatment (up to 170°C) did not significantly alter the decomposition temperature of the resin, but it may have influenced the structural properties of the material.

3.3.3 Gravimetric Thermal Analysis (GTA)

From Fig. 12, The Gravimetric Thermal Analysis (GTA) curve of dune sand and crushed dune sand reveals a gradual weight loss of approximately 0.70% as the temperature increases from 0°C to 1200°C. The initial mass loss below 200°C is primarily due to the evaporation of adsorbed water molecules on the sand particles, following the reaction H_2O (adsorbed) → H_2O (vapor). As the temperature reaches 400-600°C, a slight but continuous weight reduction is observed, corresponding to the dehydroxylation of clay minerals with the release of structural water. Additionally, the phase transition of quartz (SiO_2) from α-quartz to β-quartz occurs around 573°C, though this transformation does not contribute significantly to mass loss. In the 800-1000°C range, a more noticeable decrease in weight is attributed to the thermal decomposition of carbonate impurities, such as calcium carbonate ($CaCO_3$), leading to the release of carbon dioxide gas (CO_2):

$$CaCO_3 \rightarrow CaO + CO_2 \tag{4}$$

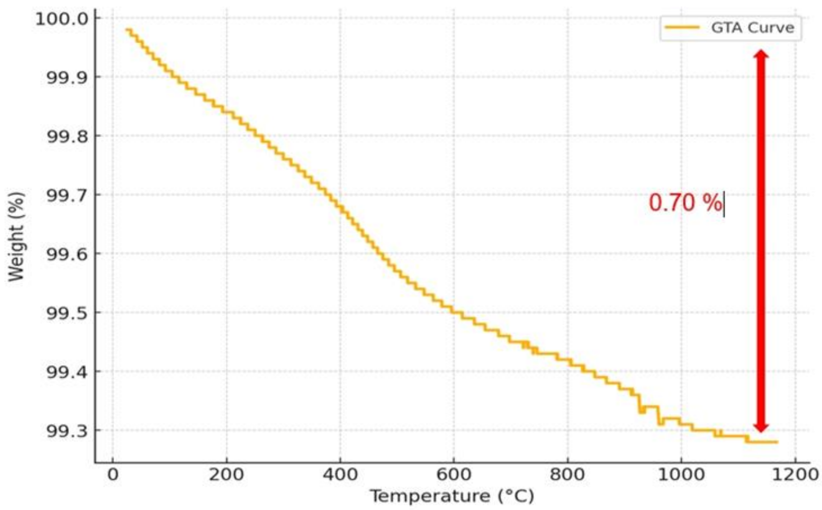


Fig. 12. Gravimetric Thermal Analysis (GTA) curve of dune sand and crushed dune sand

A significant weight loss of approximately 35% is observed in Fig. 13, primarily occurring between 200°C and 500°C, which indicates the decomposition of organic components and polymer degradation. This process is influenced by the polymerization under nitrogen gas (N_2), which creates an inert atmosphere, suppressing oxidation reactions. As a result, thermal decomposition is driven mainly by pyrolysis and volatilization rather than combustion. Beyond 600°C, the GTA curve shows mass stabilization, suggesting that the remaining material is composed mainly of silica (SiO_2) aggregates and calcium oxide (CaO), both of which demonstrate high thermal stability in this temperature range. The first stage of mass loss (below 200°C) corresponds to the evaporation of free and physically adsorbed water within the leveling mortar. As the temperature increases to 250-500°C, a sharp weight loss is observed, corresponding to the pyrolysis of the thixotropic polyester resin used in the leveling mortar. In the nitrogen environment, the polymer undergoes thermal cleavage of ester bonds (-COO-), resulting in the release of hydrocarbon volatiles, carbonaceous char, and gaseous byproducts such as CO and CO_2. The chemical degradation pathway can be approximated as:

$$(C_2H_4O)n(C_8H_6O_4)m \rightarrow CO_2 + CO + H_2 + C_xH_y + \text{char residue} \tag{5}$$

Beyond 600°C, the remaining mass stabilizes around 65%, indicating that the silica-based aggregates and calcium oxide remain thermally intact under nitrogen conditions. Unlike in an oxygen-rich atmosphere, where complete combustion of organic residues would occur, the inert nitrogen atmosphere promotes the formation of carbonaceous char, which remains in the sample instead of being oxidized into CO_2. If calcium carbonate ($CaCO_3$) is present, it may decompose at higher temperatures (~800-900°C), releasing CO_2 gas.

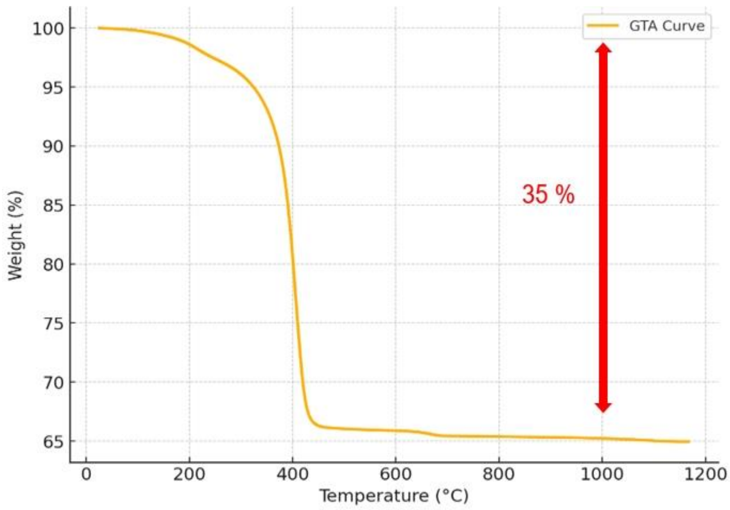


Fig. 13. Gravimetric Thermal Analysis (GTA) curve of leveling mortar and treated leveling mortar

4. Cost and Scalability

Based on the Table 5, the presented system (crushed dune sand + polyester resin + heat treatment) involves higher binder and processing costs due to the use of polyester resin (3–5 USD/kg) and thermal curing (10–15 USD/m^3), compared to the lower cost of OPC (0.1–0.15 USD/kg) and ambient curing in traditional mortars. However, the use of locally sourced dune sand—available at negligible cost—versus commercial silica sand (30–50 USD/ton), along with faster curing and significantly higher mechanical strength, may compensate for the initial investment, particularly in projects requiring high performance, reduced construction time, or limited maintenance.

Table 5. Strength of the leveling mortar after heat treatment

Component / Process	Proposed System (CDS + Polyester + Heat)	Conventional System (OPC + Silica Sand)
Binder cost	High (polyester resin ~10–20× OPC price)	Low (OPC is widely available & cheaper)
Aggregate cost	Very low (local dune sand, negligible transport cost)	Moderate (industrial-grade silica sand, often imported)
Curing time	Fast (minutes to hours post-curing)	Slow (up to 28 days for full strength)
Environmental footprint	Debatable: low transport impact, but polymer & thermal energy involved	High due to clinker production CO_2 emissions

5. Conclusions

This study demonstrated the significant potential of crushed dune sand, when combined with thixotropic polyester resin and subjected to thermal treatment, to serve as a high-performance filler in polymer-based leveling mortars. Through an integrated approach encompassing mechanical, thermal, and microstructural analyses, the research provided compelling evidence that mechanical processing and heat curing substantially enhance the composite's structural integrity and environmental viability.

The transformation of natural dune sand into angular, fractured particles via mechanical crushing not only improved surface roughness but also significantly increased the specific surface area, which in turn promoted better interfacial bonding with the resin matrix. This observation, confirmed by SEM micrographs, aligns with the conclusions drawn in earlier studies on modified desert sands, which also reported similar improvements in mechanical properties through surface alteration techniques. Thermal post-curing at 170°C was shown to further enhance the matrix's densification, as evidenced by EDS analysis indicating a marked decrease in carbon content (i.e., resin pyrolysis) and increased mineral visibility (Si, Al, Fe). This process facilitated additional cross-linking within the polyester resin, thereby reinforcing the sand–resin interface. These findings corroborate earlier thermal studies of unsaturated polyester composites, who emphasized the critical role of post-curing in improving mechanical behavior.

Mechanically, heat-treated mortars exhibited compressive strengths reaching up to 119.9 MPa and flexural strengths nearing 45.25 MPa, marking significant gains of 10–12% and up to 98%, respectively, over untreated samples. These values surpass those of conventional mortars and highlight the efficacy of combining mechanical crushing with thermal treatment for structural applications in arid regions. While prior works achieved moderate improvements through biopolymer stabilization, the current results outperform them in both compressive and flexural domains. The pronounced disparity between the gains in flexural strength (up to 98%) and compressive strength (10–12%) following thermal post-curing can be attributed to the differing failure mechanisms and stress distributions inherent in bending versus compression. Flexural strength is highly sensitive to the quality of the resin-filler interface and the ability of the matrix to transfer tensile stresses without crack initiation or propagation. Thermal treatment promotes extensive cross-linking within the polyester resin, enhances resin crystallinity, and leads to partial volatilization of weak organic phases. These changes improve matrix cohesion and significantly strengthen the interface between resins and crushed sand particles, as confirmed by SEM-EDS analyses. Moreover, the heat-induced densification process leads to better mechanical interlocking between angular filler grains and the polymer matrix, improving stress transfer pathways under tensile or flexural loading. In contrast, compressive strength is less sensitive to interfacial bonding and more dependent on the bulk resistance of the composite to axial loading. Thus, while both modes benefit from thermal treatment, the enhancement in flexural performance is more pronounced due to the microstructural reconfiguration that mitigates crack propagation and stress concentration zones, particularly in tension-dominated zones. This distinction underlines the significance of thermal curing not merely as a means of increasing bulk strength, but as a targeted strategy for improving toughness, ductility, and stress redistribution capabilities in polymer composites, especially under bending conditions.

Thermal analyses (DSC, DTA, and TGA) confirmed the composite's thermal stability up to 410°C, with consistent pyrolytic degradation behavior of the organic matrix and stable mineral structure beyond this threshold. Notably, the treated mortars retained a residual mass of ~65%, indicating high fire resistance and long-term durability. These insights position this composite as a suitable candidate for construction in high-temperature or fire-prone zones, addressing key performance demands unmet by conventional polymer concretes. From a sustainability perspective, the valorization of locally sourced dune sand not only reduces dependency on conventional aggregates but also aligns with circular economy principles by minimizing material transportation and optimizing local resource utilization. This approach directly addresses concerns raised in reviews about the environmental footprint of traditional sand-based construction.

This work contributes a scalable, cost-effective, and environmentally responsible solution for developing thermally stable, mechanically robust, and microstructurally optimized leveling mortars. Future research should explore long-term durability under environmental loading, resin modification techniques to further enhance matrix-filler compatibility, and the applicability of this approach to prefabricated structural elements. The integration of crushed dune sand and thermal treatment into mortar formulation represents not merely a technical enhancement but a strategic pathway toward resilient infrastructure in resource-constrained regions.

Practical durability tests demonstrated excellent resistance to environmental and mechanical stresses. These tests include sensitivity to mass loss, water absorption, heat treatment, and resistance to freeze/thaw cycles. The results indicate that heat treatment gives the mortars increased dimensional stability and impermeability, significantly limiting water penetration and shrinkage-related deformation. Robustness to freeze/thaw cycles confirm the composite's ability to withstand extreme climatic conditions.

The improvements in mechanical performance, particularly in flexural strength (up to 98%), were not only substantial but also statistically significant ($p < 0.05$). These findings were validated through triplicate testing and rigorous statistical analysis, reinforcing the reliability and reproducibility of the results. Despite a higher initial cost related to the use of polyester resin and heat post-treatment, the proposed system is distinguished by its rapid implementation, increased mechanical performance and the exploitation of an abundant and almost free local resource (crushed dune sand). This combination makes it an economically viable and industrializable solution, particularly for projects requiring durability, reduced construction times and minimization of transport costs.

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