

Article

Laboratory Evaluation of a Graphene Oxide–ESTEL Nanocomposite for Adobe Consolidation: Implications for Future Validation at Sudus, Saudi Arabia

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Abstract

Earthen architectural heritage is highly vulnerable to moisture, erosion, salt activity, and progressive loss of cohesion, creating a need for consolidants that improve mechanical performance without obscuring the limitations of laboratory-to-field transfer. This study evaluates a graphene oxide–ESTEL (GO–ESTEL) nanocomposite as an exploratory consolidant for adobe under controlled laboratory conditions in Egypt and discusses, separately, how the results may inform future validation at Sudus, Saudi Arabia. Laboratory specimens and non-Sodus reference adobe fragments were characterized using polarized light microscopy (PLM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), computed tomography (CT), and uniaxial compressive strength testing. A fixed exploratory formulation based on a 3 wt.% aqueous GO dispersion combined with ESTEL was applied to the adobe specimens. The treated specimens showed denser microstructural features and improved particle bridging in SEM observations, while CT imaging provided complementary qualitative visualization of the internal structure of the treated adobe. Average maximum compressive load increased from 340.60 to 486.87 kgf, corresponding to a 42.94% increase; maximum displacement and strain at failure decreased by approximately 36.8%. These results demonstrate short-term laboratory strengthening of the tested adobe formulation, but they do not establish long-term durability, an optimum GO concentration, or direct compatibility with Sudus materials. The Sudus survey is therefore retained only as an application context and monitoring framework rather than evidence of field effectiveness. Site-specific mineralogical characterization, environmental monitoring, formulation optimization, accelerated ageing, and controlled pilot trials are required before any conservation application at Sudus or comparable heritage sites.

Keywords: adobe; graphene oxide; ESTEL; consolidation; computed tomography; earthen heritage; Sudus



Academic Editor: Antonio Formisano

Received: 9 August 2026

Revised: 10 September 2026

Accepted: 14 September 2026

Published: 17 September 2026

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1. Introduction

Earthen construction is among the oldest and most geographically widespread building traditions, yet the material remains inherently vulnerable because its mechanical behavior depends strongly on particle-size distribution, clay mineralogy, pore structure, moisture state, and construction practice [1,2]. Conservation therefore requires interventions that are compatible with the original fabric and that are evaluated not only for short-term strengthening but also for water transport, ageing behavior, visual change, and long-term maintenance [3–7].

For historic adobe, deterioration commonly develops through interacting mechanisms rather than a single cause. Moisture can reduce capillary cohesion, mobilize soluble salts, and accelerate erosion [8]; wind and rain can remove surface material; and loss of protective renders or maintenance increases exposure of the earthen matrix. The conservation literature consequently emphasizes material characterization, condition assessment, preventive water management [9], compatible repair, and cautious testing of consolidants before field implementation [3–7,10].

Recent research has evaluated polymers, silanes/siloxanes, natural products, nanosilica, nano-lime, and other nanostructured systems for the protection or consolidation of earthen materials. Comparative campaigns show that treatment performance is highly substrate- and environment-dependent and that mechanical gain alone is insufficient to establish suitability; water-vapour transport, water uptake, colour, erosion resistance, and accelerated ageing are also relevant criteria [5]. In parallel, graphene and graphene-related materials have emerged as potential conservation materials because of their high specific surface area and potential reinforcing effects, although the heritage literature remains at an early stage and major questions persist regarding long-term stability, compatibility, dispersion, and structure–function relationships [11].

Sudus, a historic Najdi settlement in Saudi Arabia, was documented during a Spring 2025 field campaign using high-resolution photography, digital surveying, and three-dimensional recording. The survey identified surface erosion, loss of earthen plaster, granular disintegration, cracking, roofing loss, and localized collapse (Figure 1). These observations establish a condition baseline and a potential future monitoring framework; they do not provide material characterization or environmental measurements for the present laboratory experiment.

In this manuscript, Sudus is treated as a prospective application context rather than the source of the experimental material. The 2025 documentation records visible condition indicators and spatial damage patterns that can guide selection of future pilot areas. Causes such as moisture, salt activity, thermal cycling, and wind abrasion are discussed as plausible mechanisms supported by the broader earthen-conservation literature, but they were not directly measured at Sudus in this study.

The heritage significance of Sudus derives from its Najdi earthen architectural fabric and the traditional knowledge embodied in its material and construction systems. From a conservation perspective, however, significance does not remove the need for site-specific diagnosis [12]. Before any consolidant is considered for use, the local earth must be characterized mineralogically and physically, moisture and salt conditions must be assessed, and the treatment must be tested for compatibility, penetration, vapour transport, colour change, retreatability, and durability. The current field record is therefore used only to define the conservation problem and to support a future validation sequence, not to demonstrate the effectiveness of GO-ESTEL at Sudus.

The central research gap addressed here is methodological: although the growing literature evaluates advanced consolidants and graphene-related materials, there is still limited evidence linking nanoscale morphology, internal pore structure, and mechanical

response in adobe within one non-destructive/analytical workflow [5,11]. The present experiment combines SEM, TEM, XRD, CT, and compression testing to examine a GO-ESTEL formulation at laboratory scale. The principal contribution is therefore the integrated investigation of a proposed treatment mechanism and its short-term mechanical effect, rather than a claim of site-proven conservation performance.

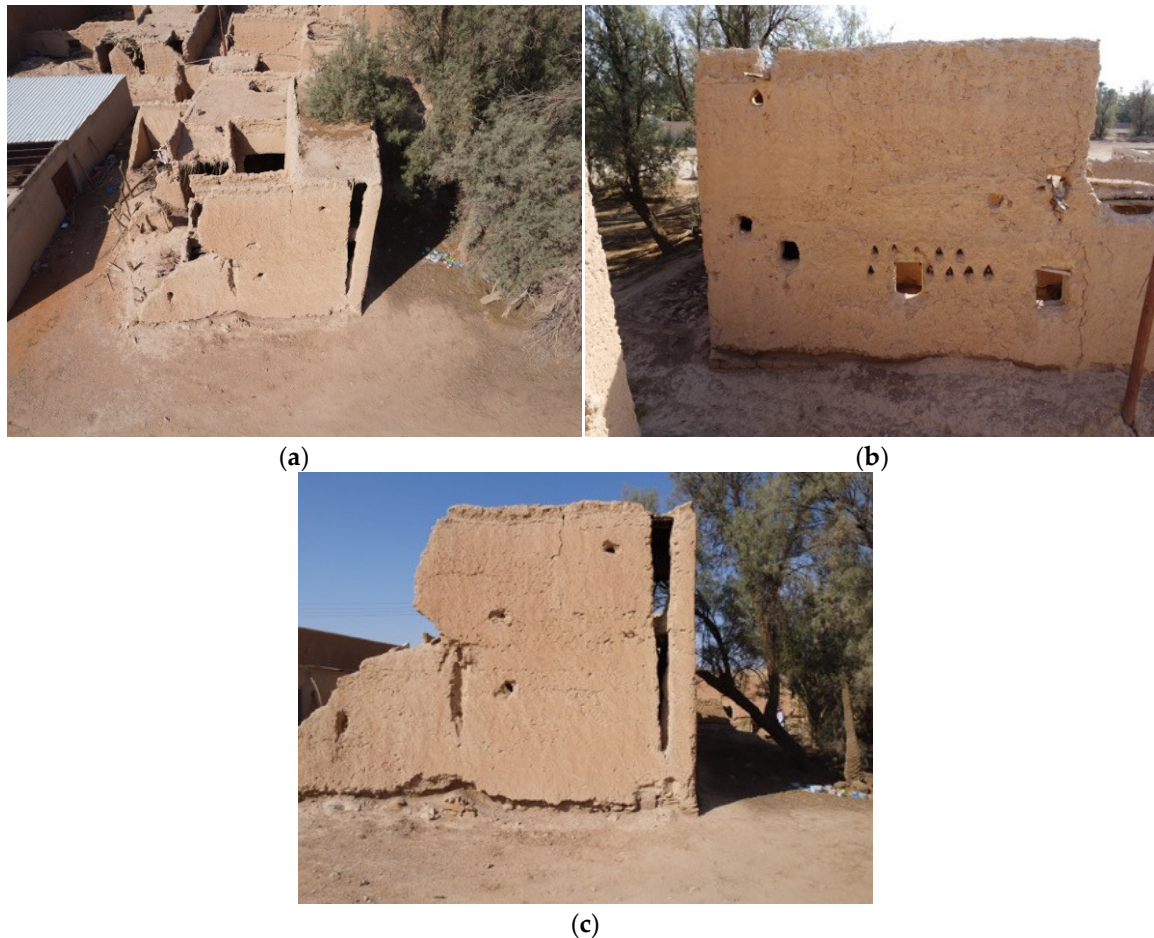


Figure 1. (a–c). Representative deterioration features observed in the historic earthen architecture of Sudus Village, including surface erosion, partial loss of earthen plaster, adobe brick disintegration, cracking, and localized structural collapse. The photographs were acquired during the Sudus field documentation campaign conducted in Spring 2025 and are presented to characterize the existing condition of the heritage structures, establish the context for the proposed future conservation application, and provide a baseline for long-term comparative assessment and monitoring.

The study further uses Sudus as a deliberately separate prospective case to illustrate how laboratory findings could be transferred responsibly: first by local material characterization, and then by small-scale compatibility and ageing tests, followed by controlled pilot application and repeated physical/digital monitoring. This staged framework responds to the established conservation principle that laboratory strengthening results should not be generalized to historic fabric without site-specific validation [5–7].

Accordingly, the novelty of this study lies in evaluating a GO-ESTEL hybrid treatment for adobe through complementary microstructural, nanostructural, tomographic, and mechanical methods, while explicitly defining the limits of transfer from Egyptian laboratory specimens to a Saudi heritage site. The study does not claim that the tested formulation is optimized or that it is presently suitable for Sudus. Instead, it establishes a proof-of-concept dataset and a testable pathway for subsequent optimization, ageing, and field validation.

2. Research Objectives

This study has three objectives: (1) to characterize the short-term microstructural and mechanical response of adobe specimens treated with a fixed exploratory GO–ESTEL formulation; (2) to examine SEM observations and qualitative CT features alongside the measured change in compressive performance; and (3) to define the additional evidence required before the treatment can be considered for pilot testing at Sudus. No claim is made that the selected GO concentration is optimal, that long-term durability has been demonstrated, or that the Egyptian specimens are materially equivalent to Sudus adobe.

3. Methodology

The research comprises two intentionally distinct components. The experimental component is a laboratory study conducted in Egypt using non-Sodus adobe materials. The contextual component is the Spring 2025 digital and visual documentation of Sudus. The two datasets are not treated as directly equivalent: the laboratory study evaluates material response under controlled conditions, whereas the Sudus record is used only to frame future compatibility testing, pilot selection, and monitoring.

3.1. Laboratory Investigation

All laboratory experiments were conducted in Egypt. The treatment trials used locally prepared adobe specimens, while a non-Sodus reference fragment from a deteriorated adobe wall in Egypt was used for cross-sectional characterization. No historic material was removed from Sudus for this study. The laboratory material should therefore be regarded as an experimental analogue rather than a material match for Sudus; site-specific mineralogical, granulometric, porosity, moisture, and salt characterization will be required before transfer of the treatment.

3.1.1. Sample Preparation for Cross-Sectional Analysis

A non-Sodus reference fragment from a deteriorated adobe wall in Egypt was used for material characterization and cross-sectional examination. This fragment was not collected from Sudus and was not used to establish compositional equivalence with Sudus adobe. It was embedded in Epoxy Resin No. 27751 using an epoxy resin-to-hardener ratio of 100:2 (*v/v*) and polished for optical and SEM examination. The representative optical micrograph is presented with the PLM results (Figure 2).

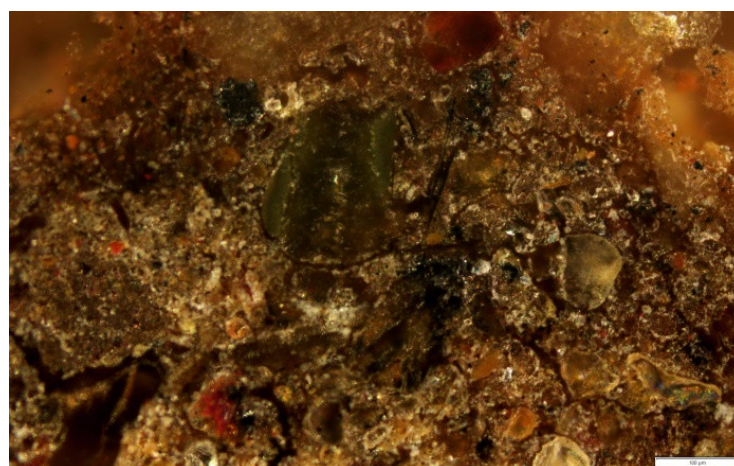


Figure 2. Polarized light micrograph of the adobe specimen illustrating its mineralogical composition, including the distribution of quartz grains, clay minerals, mineral aggregates, and organic inclusions within the earthen matrix. The image highlights the heterogeneous mineral fabric characteristic of traditional adobe and provides the basis for interpreting its microstructural behavior and durability.

3.1.2. Polarizing Microscope Investigation

The polished cross-sections of the adobe specimens were examined using a polarizing optical microscope (Olympus BX53, Olympus Corporation, Tokyo, Japan). The investigation was carried out to identify the mineralogical constituents of the adobe matrix, characterize the distribution and optical properties of the constituent phases, and evaluate the microstructural features of the earthen fabric under polarized light.

3.1.3. Scanning Electron Microscope (SEM) Investigation

The surface morphology and microstructural characteristics of the adobe specimens were investigated using a scanning electron microscope (SEM) (JEOL JSM-5500LV, JEOL Ltd., Tokyo, Japan). The analyses were performed at the Central Laboratory, Sohag University, Egypt. SEM examination provided high-resolution images for assessing particle morphology, surface texture, interparticle bonding, microcracks, pore distribution, and deterioration features, thereby establishing a detailed microstructural baseline for evaluating the effectiveness of the GO–ESTEL nanocomposite treatment.

3.1.4. Transmission Electron Microscope (TEM) Investigation

The morphology and nanostructural characteristics of the synthesized graphene oxide nanoparticles (GONPs) were examined using a high-resolution transmission electron microscope (TEM) (JEOL JEM-2100, JEOL Ltd., Tokyo, Japan). TEM analysis revealed that the graphene oxide nanosheets possessed a characteristic sheet-like morphology with an average lateral dimension ranging from 1 to 3 μm and a thickness of approximately 1–5 nm, confirming the successful synthesis of few-layer graphene oxide. These morphological characteristics are consistent with those typically reported for graphene oxide nanomaterials and provide a high specific surface area that is advantageous for interaction with the earthen matrix.

3.1.5. X-Ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was performed to characterize the crystalline structure of the synthesized graphene oxide nanoparticles. Diffraction patterns were acquired using an X'Pert PRO powder diffractometer (Malvern Panalytical, Almelo, The Netherlands) over a 2θ scanning range of $20\text{--}80^\circ$, with a minimum step size of 0.001° (2θ) and an X-ray wavelength of $1.54614 \text{ \AA}$. The graphene oxide samples were prepared and analyzed at the Central Laboratory of Nanogate Company, Cairo, Egypt. The XRD analysis was conducted to verify the crystalline characteristics of the synthesized graphene oxide and to support its physicochemical characterization prior to incorporation into the GO–ESTEL nanocomposite consolidant.

3.1.6. Computed Tomography (CT) Investigation

Computed tomography (CT) is a non-destructive imaging technique that employs an X-ray source rotating around the specimen to acquire a series of radiographic projections from multiple angles. The technique is based on the differential attenuation of X-rays as they pass through materials of varying density and composition. The transmitted X-rays are detected by an array of detectors, and the acquired projection data are computationally reconstructed into high-resolution cross-sectional images, enabling three-dimensional visualization of the specimen's internal architecture without physical sectioning [13–15].

In the present study, the adobe specimens were examined using a Toshiba Aquilion PRIME Micro-CT scanner (Model TSX-303A, Toshiba Medical Systems Corporation, Otawara, Japan; maximum input power 110 kVA). The CT examinations were carried out at the Aswan University Hospital, Aswan University, Aswan, Egypt. The reconstructed

tomographic datasets were used to examine internal attenuation variations and the distribution of visible voids in the GO–ESTEL-treated adobe, providing qualitative context for interpreting the SEM observations and mechanical response. The CT assessment does not independently measure consolidant penetration depth or treatment-induced changes in the pore network.

3.1.7. Preparation of Graphene Oxide

The discovery of new materials has frequently marked major turning points in scientific research by opening new avenues for addressing longstanding scientific and technological challenges. The isolation of graphene represents one of the most significant breakthroughs in modern materials science [16]. As a two-dimensional (2D) crystalline allotrope of carbon, graphene has attracted unprecedented research interest owing to its remarkable intrinsic properties, including exceptional mechanical strength, high specific surface area, excellent thermal conductivity, and outstanding electrical performance. Despite its relatively recent discovery, graphene and its derivatives have demonstrated a wide range of unique physicochemical characteristics that have stimulated extensive research across multiple scientific disciplines [17,18]. These properties have enabled their application in numerous advanced technologies, including nanocomposites [19–23], nanoelectronics, chemical and biosensors, rechargeable batteries, supercapacitors, hydrogen storage systems, and, more recently, conservation materials for cultural heritage, where graphene-based nanomaterials have shown considerable promise for improving the durability and performance of consolidants and protective treatments [11].

3.1.8. Preparation of the Graphene Oxide–ESTEL Nanocomposite Consolidant

The GO–ESTEL nanocomposite was prepared by dispersing graphene oxide nanoparticles in distilled water at a concentration of 3 wt.% (30 g GO per 1000 mL water), followed by 20 min of combined ultrasonic agitation and magnetic stirring. ESTEL was then added gradually, and the mixture was homogenized for a further 20 min. The 3 wt.% GO dispersion was used as a fixed exploratory formulation for this proof-of-concept experiment. The study was not designed as a concentration-optimization or dose–response investigation; accordingly, the selected ratio must not be interpreted as optimal. Future work should compare multiple GO concentrations and GO:ESTEL proportions using mechanical, hygric, colour, penetration, and ageing criteria before a field formulation is selected.

3.1.9. Mechanical Testing

Uniaxial compression testing was used to compare the load-bearing response of untreated and treated adobe specimens. Compressive stress was calculated as $\sigma = P/A$, where P is the applied load and A is the loaded cross-sectional area. The specimens measured $3 \times 3 \times 3$ cm and were centered on the loading platen before loading to failure. Three specimens were tested in each condition; Table 1 reports the average values available from the experimental record.

Because the available experimental record provides group averages rather than the individual replicate values, the present manuscript reports the observed percentage changes descriptively and does not claim inferential statistical significance. Reporting individual replicate values, dispersion measures, and statistical tests is recommended for the next experimental phase.

Table 1. Average uniaxial compression results for three untreated and three GO–ESTEL-treated adobe specimens. Individual replicate values were not available in the present dataset; results are therefore interpreted descriptively.

Property	Control Specimen (Before Treatment) Average of Three Samples	Strengthened Specimen (After Treatment) Average of Three Samples	Percentage Change
Maximum Force (kgf)	340.60	486.87	+42.94%
Maximum Stress (kgf/mm ²)	0.13762	0.19671	+42.94%
Maximum Stroke (mm)	2.880	1.820	−36.8%
Maximum Strain (%)	6.40	4.04	−36.8%

3.1.10. Treatment Procedure

Based on the results of the preliminary investigations, the adobe specimens were treated according to the following conservation protocol:

- (a) Pre-consolidation: Fragile areas were temporarily stabilized using Japanese tissue paper impregnated with the consolidating formulation to protect weakened surfaces during treatment.
- (b) Mechanical cleaning: Following pre-consolidation, loose surface deposits and accumulated dust were carefully removed using a controlled air blower to prepare the specimens for consolidation.
- (c) Consolidation treatment: The GO–ESTEL nanocomposite was applied by repeated brushing over three consecutive days to ensure adequate penetration and uniform distribution throughout the adobe matrix. After each application, the treated surfaces were covered with polyethylene sheets to minimize solvent evaporation and promote effective curing of the consolidant, thereby enhancing the long-term stability of the treated adobe specimens.

4. Results

4.1. Deterioration Mechanisms of the Historic Earthen Buildings in Sudus Village

The Sudus survey documented visible condition features including basal and surface erosion, loss of earthen plaster, granular disintegration, cracking around openings, loss of roofing elements, and localized collapse. These were measured as field observations in the sense of photographic and geometric documentation. The survey did not include in-situ mineralogical, moisture, salt, or climatic measurements; therefore, causal attributions are not presented as measured results.

Potential mechanisms such as moisture ingress, salt crystallization, thermal cycling, and wind-driven abrasion are retained only as literature-supported hypotheses that may explain some observed patterns and that should be tested in future site-specific investigations [3–5,7,10]. This distinction prevents the Sudus observations from being used as direct validation of the laboratory treatment.

4.2. Polarizing Microscope (PLM) Investigation

Polarized light microscopy (PLM) is an essential analytical technique for identifying the mineralogical constituents and evaluating the microstructural characteristics of adobe materials. Examination of the adobe cross-sections using a polarizing light microscope (PLM) revealed that the earthen matrix is composed predominantly of quartz grains, mineral aggregates, clay minerals, and straw fibers, the latter serving as a traditional organic reinforcing and binding material within the adobe matrix. The quartz

grains exhibit irregular morphology and are embedded within a clay-rich matrix, while the randomly distributed straw fibers contribute to the cohesion of the earthen fabric but also introduce additional pore spaces. The heterogeneous distribution of mineral particles and organic inclusions produces an inherently porous microstructure, which facilitates moisture migration and increases the susceptibility of the adobe to weathering and mechanical deterioration. This high degree of porosity is considered one of the principal factors controlling the durability and mechanical performance of the material, thereby highlighting the necessity of consolidation treatments capable of enhancing interparticle bonding while reducing pore connectivity. The representative mineralogical composition and microstructural characteristics observed under polarized light are presented in Figure 2.

4.3. Scanning Electron Microscope (SEM) Investigation (Before Treatment)

Scanning electron microscopy (SEM) observations of the untreated adobe specimens revealed extensive microstructural deterioration associated with prolonged weathering. The micrographs showed numerous interconnected pores, microcracks, and voids distributed throughout the earthen matrix, indicating a highly porous and weakened internal structure. These defects are considered pathways for moisture migration and contribute significantly to the progressive deterioration of adobe materials. In addition, SEM examination demonstrated clear evidence of deterioration affecting the principal constituents of the adobe, including quartz grains, clay minerals, and the organic straw fibers incorporated as traditional reinforcing material. Quartz grains exhibited surface weathering and partial detachment from the surrounding clay matrix, while the clay minerals showed signs of disintegration and loss of cohesion. The organic straw fibers also displayed advanced degradation, resulting in the formation of additional voids and a reduction in interparticle bonding within the earthen fabric. Collectively, these microstructural alterations explain the reduced mechanical integrity and increased susceptibility of the untreated adobe to environmental deterioration. Representative SEM micrographs illustrating these deterioration features are presented in Figure 3.

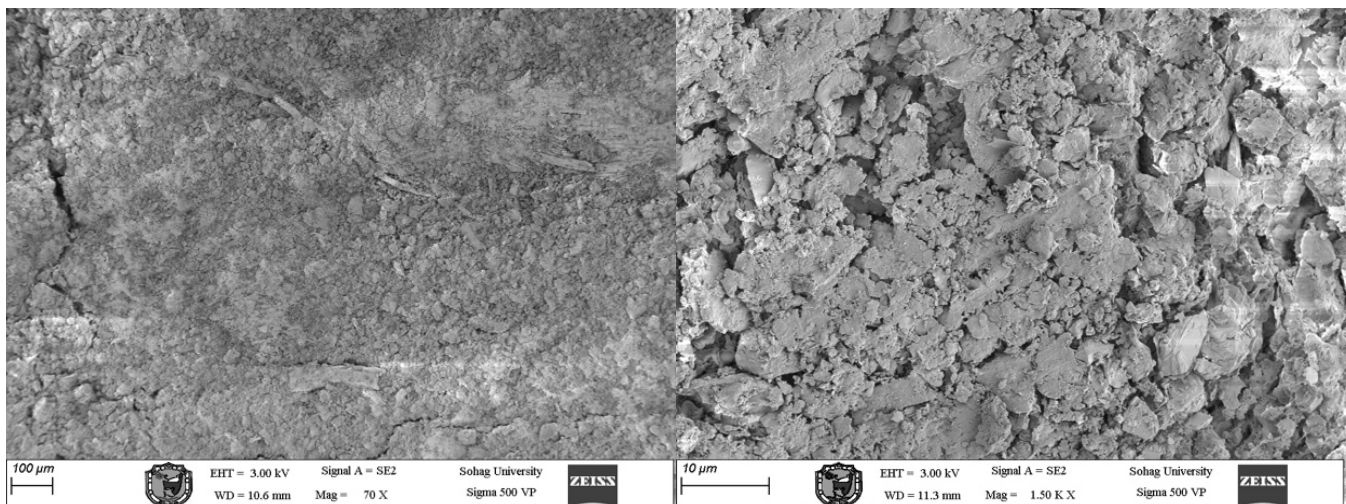


Figure 3. SEM micrographs of the untreated adobe specimen showing extensive microstructural deterioration, including interconnected pores, microcracks, and pronounced weathering of quartz grains resulting from long-term weathering processes. The images illustrate the deterioration of the earthen matrix and the loss of interparticle cohesion, providing evidence of the progressive degradation mechanisms responsible for the reduced structural integrity of the adobe material prior to consolidation treatment.

4.4. Scanning Electron Microscope (SEM) Investigation (After Treatment)

SEM examination of the treated adobe specimens demonstrated a marked improvement in the microstructural integrity of the earthen matrix following the application of the graphene oxide nanoparticle (GONP)–ESTEL nanocomposite. The micrographs revealed a uniform distribution of the nanocomposite over the specimen surface, together with effective penetration into microcracks, pores, and intergranular spaces within the adobe matrix.

The deposited nanocomposite formed continuous bridges between mineral particles, enhancing interparticle cohesion and reducing pore connectivity. Consequently, the treated specimens exhibited a denser and more compact microstructure, with a noticeable reduction in the size and number of microcracks and surface voids compared with the untreated samples. These observations indicate that the GO–ESTEL formulation effectively infiltrated the earthen matrix and contributed to improving its structural continuity, thereby providing a plausible microstructural explanation for the anticipated enhancement in the mechanical performance of the treated adobe. Representative SEM micrographs illustrating the morphology of the treated specimens are presented in Figure 4.

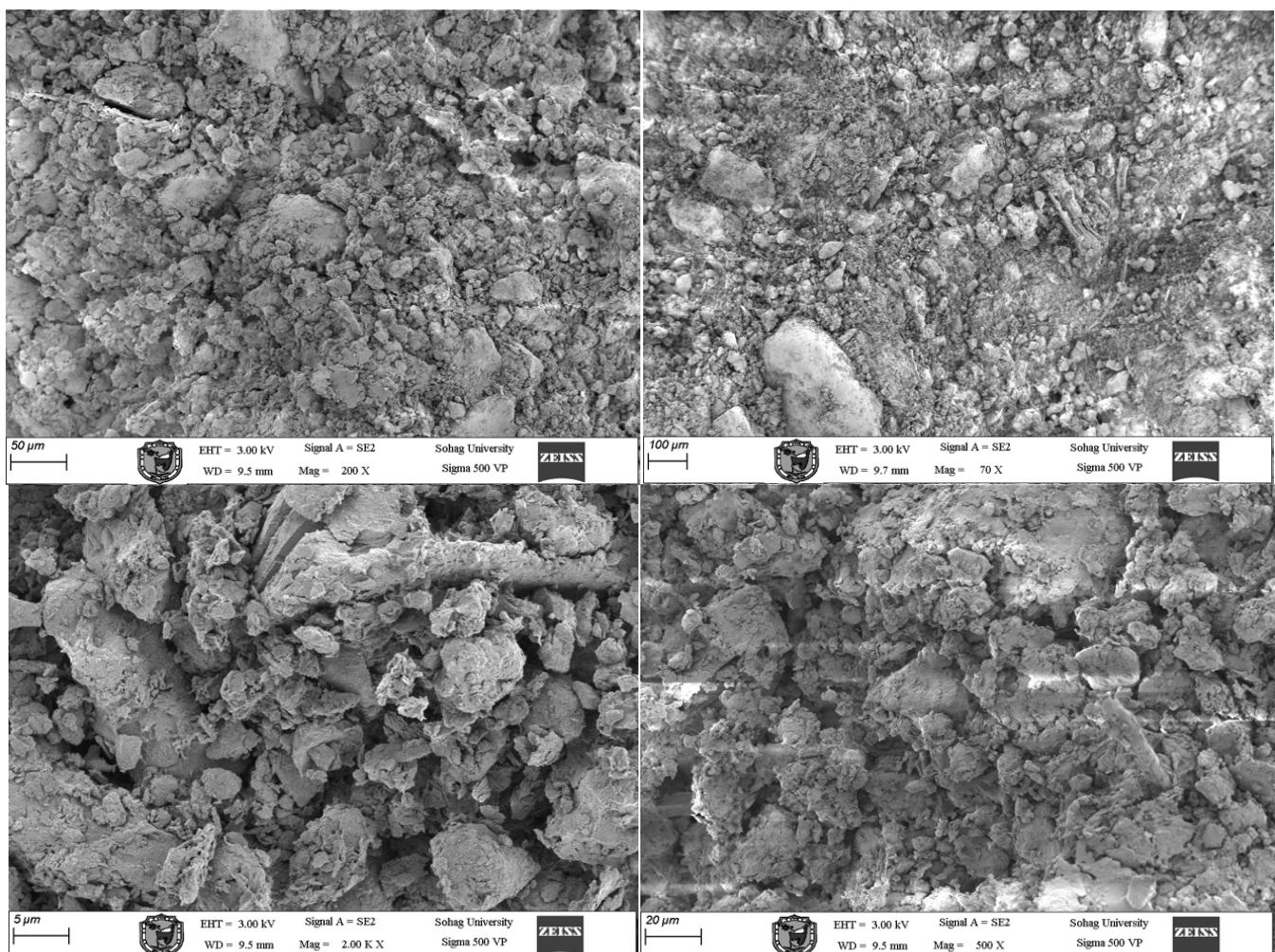


Figure 4. SEM micrographs of the treated adobe specimen illustrating the homogeneous distribution of the graphene oxide nanoparticle (GONP)–ESTEL nanocomposite over the surface of the adobe matrix. The images demonstrate effective penetration of the consolidant into pores and microcracks, the formation of bridges between mineral particles, and the development of a denser, more coherent microstructure following treatment.

4.5. Transmission Electron Microscopy (TEM) Results

TEM imaging of the prepared graphene oxide showed thin, wrinkled, sheet-like nanosheets characteristic of few-layer GO. The observed morphology is consistent with the high surface-area, layered structure expected to promote interaction with a porous matrix. TEM characterizes the GO nanomaterial itself; it does not demonstrate penetration or durability within adobe. Representative images are shown in Figure 5.

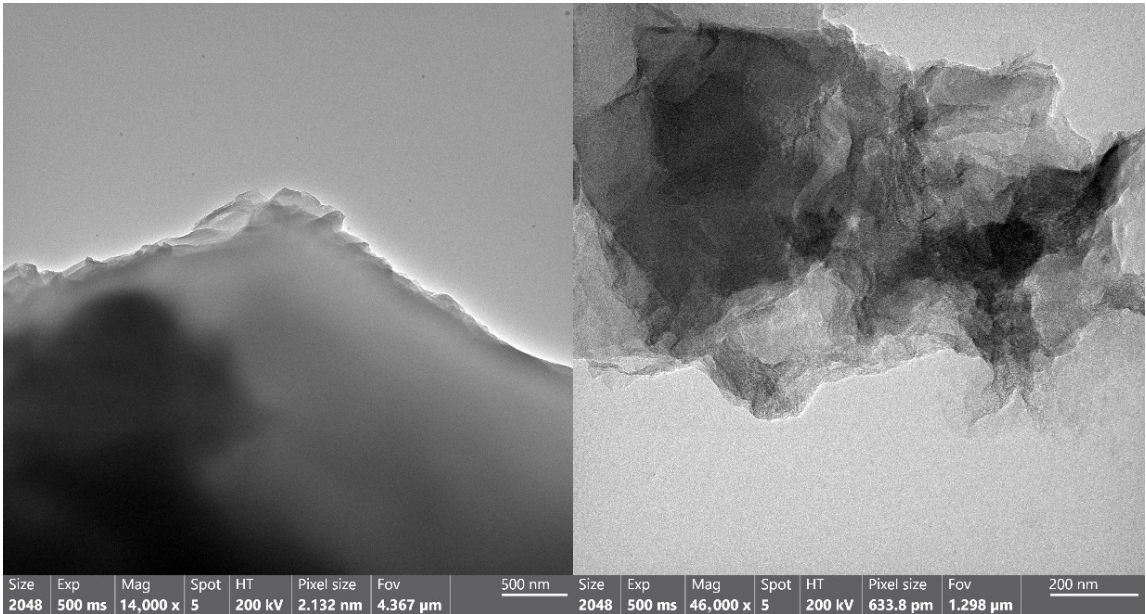


Figure 5. TEM images of the prepared graphene oxide, showing thin, wrinkled sheet-like nanosheets typical of few-layer GO.

4.6. X-Ray Diffraction (XRD) Results

The XRD pattern of the synthesized graphene oxide is presented in Figure 6. The diffractogram was used to verify the crystalline characteristics of the prepared GO prior to incorporation into the hybrid consolidant. Interpretation is limited to material characterization and is not used to infer the mineralogical composition of Sudus adobe.

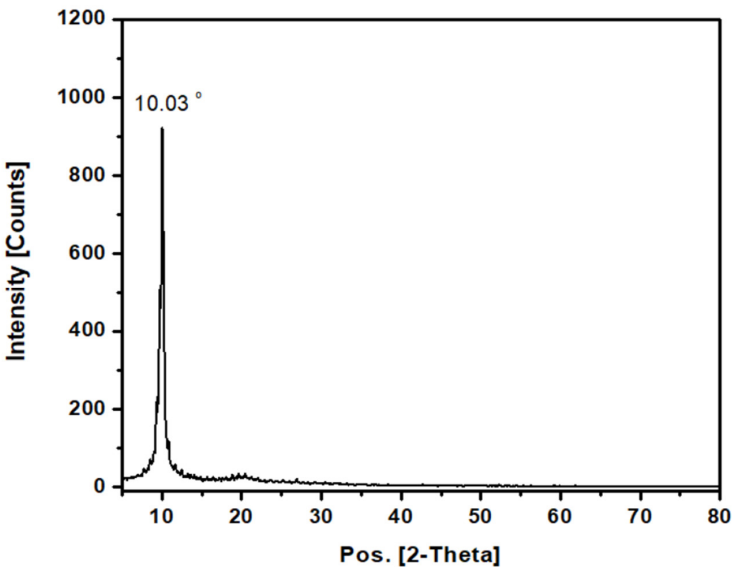


Figure 6. XRD pattern of the synthesized graphene oxide used in the GO–ESTEL formulation.

4.7. Computed Tomography (CT) Results

CT provided non-destructive three-dimensional visualization of internal attenuation variations, voids, and pore-related features in the GO-ESTEL-treated adobe (Figure 7). The reconstructed images document the internal heterogeneity of the treated material and complement the SEM and mechanical findings used to interpret the proposed consolidation mechanism. An untreated CT comparison image is not available for inclusion; consequently, these images do not independently establish before-and-after changes in density, pore connectivity, or consolidant penetration. Because the present dataset does not include a validated segmentation protocol or complete quantitative pore-volume statistics, the CT evidence is interpreted qualitatively rather than as a definitive quantitative porosity measurement.



Figure 7. Representative CT sections of GO-ESTEL-treated adobe showing internal attenuation variations and visible void-related features. The images provide qualitative structural information for the treated material only; no untreated CT comparison is presented.

4.8. Uniaxial Compressive Strength (UCS) Results

The uniaxial compressive strength (UCS) is one of the most important mechanical parameters for evaluating the load-bearing capacity and structural performance of adobe materials. It represents the maximum compressive stress that an adobe specimen can withstand under uniaxial loading and provides a reliable indicator of the effectiveness of consolidation treatments. The UCS tests were performed using a universal compression testing machine on standardized adobe specimens measuring $3 \times 3 \times 3$ cm. To evaluate the effectiveness of the proposed consolidant, the study included untreated control specimens and specimens treated with the graphene oxide nanoparticle (GONP)–ESTEL nanocomposite.

The treated group showed higher average maximum load and calculated compressive stress than the untreated group. Average maximum load increased from 340.60 to 486.87 kgf (+42.94%), while maximum stroke and strain at failure decreased by approximately 36.8% (Table 1; Figure 8). These results indicate a stronger and stiffer response under the tested short-term conditions. Because only group averages are available in the current record, the manuscript does not describe this change as statistically significant and does not generalize it beyond the tested formulation and specimens.

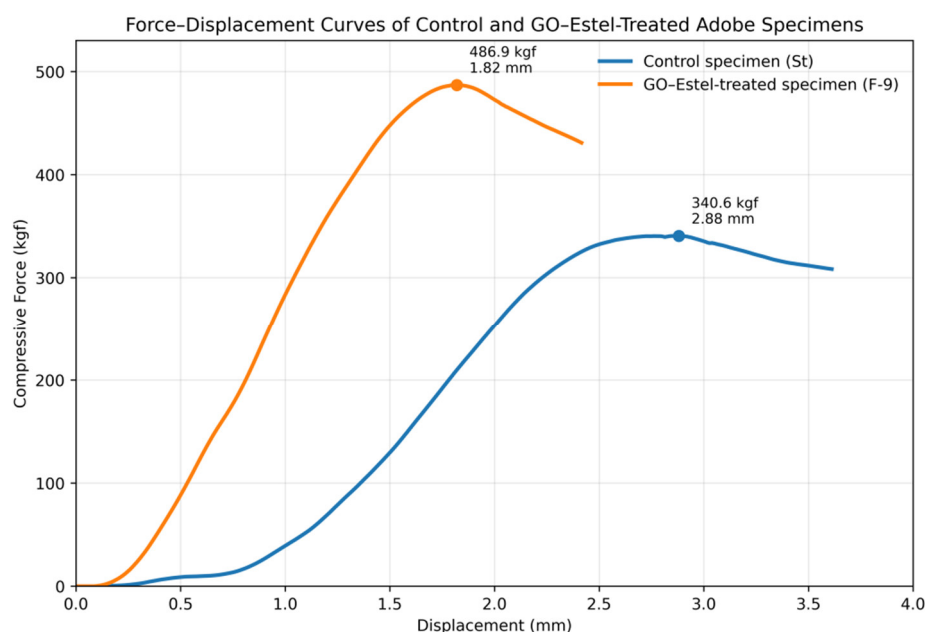


Figure 8. Representative force–displacement comparison for untreated and GO–ESTEL-treated adobe. The reported group-average maximum load increased from 340.60 to 486.87 kgf after treatment.

5. Discussion

The results support a short-term laboratory strengthening effect of the GO–ESTEL treatment, but several issues limit interpretation. First, the material tested in Egypt was not sampled from Sudus, so the laboratory response cannot be assumed to represent the mineralogical or hygric behavior of the Saudi heritage fabric. Second, only one fixed formulation was tested. The experiment therefore demonstrates feasibility, not optimization. Third, the study did not include accelerated ageing, wet–dry cycling, salt crystallization, vapour-permeability testing, colour measurement, or retreatability assessment, all of which are important for conservation compatibility [5,11].

Within these limits, the analytical methods provide complementary evidence. SEM observations suggest improved particle bridging and a denser treated microstructure; CT visualizes internal structural heterogeneity and visible voids in the treated adobe; and compression testing shows a 42.94% increase in average maximum load. The SEM and

mechanical findings support a plausible consolidation mechanism based on penetration, pore modification, and enhanced interparticle bonding, with CT providing complementary structural context rather than an independent demonstration of treatment-induced changes. This interpretation remains insufficient to establish long-term durability.

The reduction in maximum stroke and strain at failure also indicates increased stiffness. This can be beneficial for load-bearing capacity, but in heritage conservation an increase in stiffness must be evaluated cautiously because excessive local stiffness or gradients between treated and untreated zones can create incompatibility and stress concentrations. Future experiments should therefore assess not only strength gain but also elastic response, moisture transport, treatment depth gradients, and behavior at treatment boundaries.

The current formulation should be compared with alternative GO concentrations, ESTEL-only controls, GO-only controls, and other consolidant systems. Such comparative testing would establish whether the hybrid formulation provides a meaningful advantage over the carrier/consolidant alone and would permit identification of a minimum effective concentration. This is particularly important because recent conservation studies emphasize that treatment selection should balance mechanical improvement with water behavior, vapour permeability, colour stability, erosion resistance, and ageing performance [5].

Long-term performance remains unresolved. Accelerated ageing under wet–dry cycles, salt exposure, thermal cycling, and UV/environmental exposure should precede any field application. The emerging literature on graphene-related materials in cultural heritage likewise identifies long-term stability, physicochemical compatibility, dispersion, and structure–function relationships as priority research needs [11].

5.1. Implications for Future Validation at Sudus

The Sudus documentation is best understood as a future validation framework rather than part of the laboratory proof. Before pilot treatment, Sudus adobe should be characterized for mineralogy, particle-size distribution, porosity, soluble salts, moisture behavior, and existing surface treatments. Representative mock-ups or sacrificial detached material should then be used for formulation screening and ageing. Only after acceptable compatibility results should a small, reversible, well-documented pilot area be selected.

If a pilot proceeds, repeated photogrammetry or laser scanning can provide geometric monitoring of surface loss and crack evolution, but such digital monitoring should complement rather than replace material and environmental measurements. This staged sequence directly addresses the laboratory-to-site gap and prevents the present laboratory results from being interpreted as evidence of field efficacy.

5.2. Limitations

The study has several principal limitations: the experimental adobe is not sourced from Sudus; only one GO–ESTEL formulation was tested; the available mechanical record contains group averages rather than individual replicate values; and no accelerated ageing or long-term field exposure was undertaken. An untreated CT comparison image is also unavailable, so the CT results cannot demonstrate treatment-induced changes directly. The observed improvements therefore establish short-term proof of concept only. These limitations define the experimental priorities for the next phase rather than weakening the descriptive validity of the present measurements.

6. Conclusions and Future Research

This proof-of-concept study evaluated a fixed GO–ESTEL formulation for laboratory consolidation of adobe. Under the tested conditions, treated specimens exhibited denser microstructural features and higher average compressive capacity, with maximum load

increasing by 42.94% and maximum stroke/strain decreasing by approximately 36.8%. SEM and mechanical observations are consistent with enhanced interparticle bonding and a proposed modification of the pore network; CT provides complementary qualitative information on the internal structure of the treated adobe.

These results are promising but deliberately limited. They do not demonstrate an optimum formulation, long-term durability, statistical significance, or direct compatibility with Sudus adobe. The Sudus survey is therefore presented only as a prospective application context and as a baseline for future pilot selection and monitoring.

Before any site application, future work should: characterize Sudus material and environment; compare multiple GO concentrations and GO:ESTEL ratios; include ESTEL-only and GO-only controls; report individual replicate data and statistical uncertainty; obtain paired untreated/treated CT images with validated image analysis; evaluate water absorption, vapour permeability, colour, salt and wet-dry resistance, ageing, and retreatability; and conduct a small controlled pilot followed by long-term material, environmental, and digital monitoring.

The principal contribution of this study is therefore an integrated laboratory characterization workflow for a GO–ESTEL/adobe system and a conservative framework for translating laboratory evidence into heritage practice. The treatment should be considered a candidate for further investigation, not a field-ready conservation solution.

Author Contributions: Conceptualization, A.S., R.A. and S.B.A.; methodology, A.S., A.S.A., S.B.A. and R.I.; laboratory investigation and formal analysis, A.S.; Sudus case-study framing, heritage-conservation interpretation and digital monitoring framework, S.B.A.; digital data processing, three-dimensional modelling, data curation and visualization, R.I.; writing—original draft, A.S. and A.S.A.; writing—review and editing, A.S., S.B.A. and R.I.; supervision and project administration, A.S. and S.B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors gratefully acknowledge The Royal Institute of Traditional Arts (Wrth). They also thank the Higher Diploma in Digital Heritage cohort at the institute for their contribution to the Sudus field documentation during the Spring 2025 fieldwork.

Conflicts of Interest: The authors declare no conflicts of interest.

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