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Enhancing Sustainable Construction: An Evaluation of Nano-Graphene's Effectiveness in Mortar Composition

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Abstract

This study examines the effectiveness of adding graphene nanoparticles to plaster mortars, assessing both their mechanical and economic influence. The base materials were characterized, complying with relevant standards, and a Type S standard mortar was designed, which not only met but exceeded the minimum regulatory requirements for strength and adhesion. Experiments were conducted with four concentrations of graphene nanoparticles, comparing them with pre-mixed blends and an in-situ mix. The tests revealed that adding 0.25% graphene significantly optimizes compressive strength and adhesion without compromising workability. Higher concentrations of graphene were found to negatively impact these properties. Cost analysis identified that the mix with 0.25% graphene offers the best cost-benefit ratio for plaster applications.

1. Introduction

The mortar has played a fundamental role in construction throughout history. As described by Chudley and Greeno (2006), this material has been an essential component for bonding a variety of elements, such as bricks, stones, and blocks. In recent years, the increase in the use of structural masonry and its impact on the construction of civil works, particularly in buildings, has led to a significant rise in the demand for mortar, both for bonding and for plastering or rendering. However, unlike concrete, which has well-established protocols for its production, specific technical design and quality control

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procedures for mortar have not yet been developed, representing a challenge in ensuring its excellence in modern constructions (Mahdi Feizbahr et al., 2013; Rivera, 2009).

Nanotechnology and recent advancements in the building industry have made it feasible to produce materials that are lighter, more resilient, and stronger than steel. This technology has been applied in the production of stronger concretes, thus contributing to the improvement of infrastructure and buildings (Alvansaz, Arico, et al., 2022; Alvansaz, Bombon, et al., 2022; Mohammafarid Alvansazyazdi & Rosero, 2019; Asli & Arabani, 2022; Cervantes Calvo, 2011; Meqdad Feizbahr & Pourzanjani, 2024). Among the different types of nanomaterials investigated, six of them are the most popular in the industry: Nano-silica, Nano-titanium dioxide, Nano-magnetite, Nano-calcium carbonate, Nano-aluminum trioxide, and Carbon nanotubes (Alvansaz, Bombon, et al., 2022; Meqdad Feizbahr & Pourzanjani, 2024; Mahdi Feizbahr et al., 2020; Prieto & Castellanos, 2017). Graphene nanoparticles are a form of carbon with a unique molecular structure that includes graphite, graphene oxide, and graphene nanoplatelets which exhibit exceptional properties such as high electrical and thermal conductivity, and remarkable mechanical strength. These characteristics, along with their ability to gas-repelling and chemical resistance, make them a considerable candidate for innovative applications, including their use as an antibacterial compound (Mohammadfarid Alvansazyazdi et al., 2023; Mittal et al., 2020).

The aim of this experimental research is to investigate the effect of graphene nanoparticles on ordinary mortar, concentrating on measuring compressive strength and adhesion in mortar used for plastering works. A mix involving traditional materials such as cement, fine aggregate, and water was designed, leading to extensive comparisons between the properties of conventionally made on-site mortar, prefabricated mortars, and the graphene-enriched mortar variation. This allowed for the evaluation of graphene's efficacy as an additive in mortars and its potential to revolutionize this aspect of the construction industry.

2. Mortars and Graphene Nanoparticles

2.1. Mortars

2.1.1. Definition and Types of Mortars

Mortar is typically defined as a homogeneous mixture containing a binding substance, a filler component (such as fine aggregate or sand), water, and occasionally additives. Essentially, mortar can be considered a type of concrete, but without the use of coarse aggregates. It is widely employed for joining bricks during the construction of masonry walls or for covering them, in which case it is referred to as plaster or render (Gutiérrez de López, 2003; Guzmán, 2001). The Ecuadorian Technical Standard (NTE – INEN 2 518: 2010), classifies mortars according to their properties and applications by assigning them a specific letter. These letters are M, S, N, O, and K, which correspond to the spelling of every two letters of the English word "MaSoN wOrK," meaning masonry or stonework (INEN, 2010).

2.1.2. Classification of Mortars

There are two categories of mortars, based on their hardening reference, include aerial mortars, which harden in the air as water evaporates, resulting in a slow setting through carbonation, and hydraulic mortars, which harden under water due to their composition, enabling them to achieve considerably high initial strengths (Cabral et al., 2023). Mortars can also be classified as Wet and Dry. Wet mortars are prepared or mixed at the plant, featuring enduring characteristics that allow them to be stored fresh for up to 48 hours. Their setting process initiates upon contact with masonry. Conversely, pre-mixed dry mortars are also prepared at the plant but are finalized at the construction site by adding the recommended amount of water (Salamanca Correa, 2001).

2.1.3. Components of Mortar

The key components of mortar include cementitious material (such as Portland cement), aggregates, water, and additives. The specifications of these components are governed by technical standards such as NTE INEN 2518:2010 (INEN, 2010).

- Cementitious Material

The NTE IN EN 2 518 (INEN, 2010) describes various cementitious materials, such as: Portland cement, composite hydraulic cements, hydraulic cements, and Portland cement with blast furnace slag. These are distinguished by their types and, in certain situations, by their uses.

- Aggregates

Aggregates used in mortar production are obtained from the fragmentation of rocks. They serve to reduce the contraction of the mortar, additionally favoring carbonation and increasing the porosity of the conglomerates. This allows the carbon dioxide in the air to easily penetrate the mass, stabilizing its volume. The proper selection of the type of aggregate is crucial when seeking to adjust the mortar's texture (Adeyi et al., 2019).

- Water

The water used in the manufacture of mortars and concretes must be potable. Liquids with sugars such as sucrose or glucose should not be used. If water from sources is used, it must comply with NTE INEN 2617: 2012 ((2012), 2012). If the water does not meet quality specifications, ASTM 33 allows for a comparative test. If the water under study achieves at least 95% of the strength obtained with distilled water in 7 days, it is considered suitable for mixing (C33/C33M, 2008).

- Additives

In the construction industry, additives can be presented in solid or liquid states, which are incorporated into concrete, cement, and mortar in small amounts based on the weight of the cement. Their main function is to modify or improve the properties of mortars and concretes. These modifications can be observed when the material is in a fresh or hardened state. Additives should not be introduced into the mortar unless specified. Additives should not contain more than 65 ppm (0.0065%) of water-soluble chloride or more than 90 ppm (0.0090%) of acid-soluble chloride, of the total chloride in the mortar, unless clearly stipulated in contractual agreements. Among these types of additives for mortars are: adhesion enhancers, workability optimizers, setting accelerators, setting retarders, and water repellents that must comply with ASTM C 1384 (Española, 1899; Kujawa et al., 2021).

2.1.4. Properties of Mortars

In their plastic state, mortars exhibit a series of key properties that are essential for determining their behavior and effectiveness during fabrication and application in construction. Among these properties, workability and consistency are fundamental to ensure efficient handling and uniform application of the mortar, thus assuring the quality of construction work. On the other hand, when the mortar reaches its hardened state, its quality and functionality are primarily assessed through two critical properties: strength and adhesion. The strength of the mortar defines its ability to withstand loads and pressures without fracturing or deforming, which is crucial for the structural integrity of the construction. Adhesion, meanwhile, refers to the mortar's ability to remain firmly attached to different construction materials, such as bricks or blocks, which is vital for the durability and stability of structures (Bos et al., 2016; Paul et al., 2018; Zahra et al., 2021).

2.1.5. Prefabricated Mortars

Prefabricated mortars are pre-prepared mixes of materials like cement, sand, additives, and water, manufactured under controlled conditions off the construction site. These mortars are prepared in advance at a production plant and then transported to the job site in the form of panels, blocks, or other prefabricated elements. Prefabricated mortars offer advantages such as precision in material dosing, uniformity in quality, reduction in construction times, and optimization of resources. These products are used in various construction applications, such as coatings, walls, partitions, or structural elements, and can be obtained in different presentations (Mohammadfarid Alvansazyazdi et al.; Babaev et al., 2020).

2.2. Nanotechnology and Nanomaterials

Nanotechnology, a field of study and technological development that operates at the smallest conceivable scale, is defined as the manipulation and use of materials and structures whose size is measured in nanometers, that is, in atomic and molecular dimensions. According to the Real Academia Española (Española, 1899), this technology focuses on the management of materials and structures at this nano-scale. Expanding this definition, NIH highlights the potential of nanotechnology to develop innovative applications in a variety of fields, including genomics, engineering, computer science, and medicine, thanks to its ability to manipulate matter at the nanometric level. Ventura (Ventura, 2012) adds that this applied science allows the creation of devices, materials, and structures with unique and beneficial properties at this scale. Together, these definitions converge on characterizing nanotechnology as a science dedicated to the manipulation of materials and structures at the nanometric scale, with extensive and diverse applications in various industrial fields (Conley et al., 2023; Dulta et al., 2022).

2.3. Graphene Nanoparticles

2.3.1. Background

Graphene, a substance initially described in the 1930s and whose term was officially recognized in 1994 as a single layer of graphite, has emerged as a revolutionary material in various scientific disciplines and industrial applications(Saldivar, 2014). Despite its historical knowledge, it was not until 2004 that Andre Geim and Konstantin Novoselov from the University of Manchester succeeded in isolating an individual layer of this material, marking a milestone in graphene research and technology and earning the Nobel Prize for their discovery (Thakur & Thakur, 2018).

Graphene is characterized as a carbon allotrope in a two-dimensional structure. With a thickness of only one atom, this material presents a diversity of molecular structures and unique properties, depending on the number of layers composing it, which vary from single layers to more complex multi-layer structures(Paul et al., 2018). In Figure. 1, graphene is shown as the mother of all forms of graphite, i.e., a two-dimensional construction material for carbonaceous materials of all other dimensions, which can be curved into 0D (fullerenes), 1D (rolled into nanotubes), and 3D (applied in graphite).

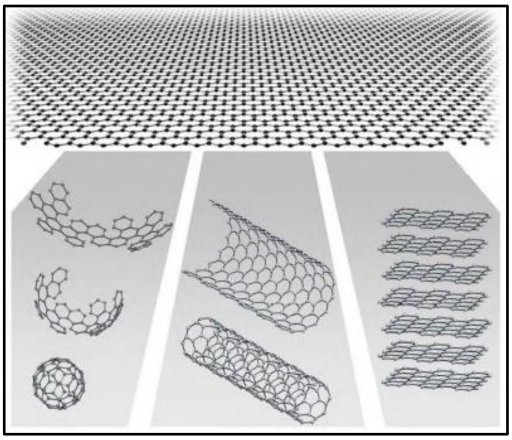

Figure 1. Mother of all forms of graphite (Giraldo, 2011).

This material stands out for its transparency, flexibility, extreme strength, impermeability, and a capacity for electrical conduction superior to any other known metal (SERNA JARA, 2021).

Advances in experimentation and practical application of graphene have demonstrated its great potential, particularly in electronic and automotive engineering, as well as in the construction field. It has been observed that graphene can significantly improve the strength and sustainability of concretes and other construction composites (Sardar Kashif, 2018). Despite its growing popularity in regions like Asia, Europe, Oceania, and North America, interest in Latin America has been more limited, largely due to a lack of investment in the mining sector. However, some countries in the region, such as Peru, Colombia, and Chile, are beginning to explore the possibilities of graphene in research (Ortega San Martín & Hernández Cenzano, 2021).

In Ecuador, studies like those conducted on Villonaco Hill in Loja have explored obtaining graphene oxide from graphitic schists to strengthen mortars and other cementing compounds. These investigations have shown an increase in the mechanical strength of mortars with the addition of graphene oxide, evidencing the broad spectrum of applications and benefits of graphene in construction and other areas (Ávila Espinoza, 2018).

2.3.2. Methods of Obtaining Graphene

Graphene can be obtained through various methods. Among them, the physical method or "tape method" is notable for its simplicity and effectiveness. This process, employed by University of Manchester researchers Andre Geim and Konstantin Novoselov, involves the mechanical exfoliation of graphite layers to obtain graphene sheets. Despite its efficiency in producing high-quality graphene, this method is slow and impractical for large-scale applications. Alternatively, chemical methods of graphene production offer a different approach. These methods, which include both top-down and bottom-up techniques, allow the production of graphene from carbon sources, such as natural graphite. While top-down methods reduce larger materials to nano-scale, bottom-up methods build the graphene structure from smaller blocks (Nanotechnologies, 2017). These methods vary in terms of complexity, cost, and the quality of the produced graphene, being selected based on the specific needs of the application and the desired scale of production.

3. Materials and Methodology

In this study, the characterization of various materials used in the manufacture of mortar specimens for construction was carried out. The materials under study are fine aggregate (sand), cement, and graphene nanoparticles. The characterization was conducted through laboratory tests that comply with national NTE INEN standards, as well as international ASTM and UNEN-EN standards.

Additionally, the process of dosing and manufacturing the mortar specimens is detailed, followed by the presentation of the results obtained from the tests performed on the mortars both in fresh and hardened states. Among the tests conducted are the measurement of fluidity, simple compressive strength at 24 hours, 3 days, 7 days, and 28 days, and adhesion strength at 28 days. These results are thoroughly analyzed and interpreted.

It is important to highlight that the development of the research relied on the use of the materials detailed in Table 1, which played a fundamental role in the process of characterization and evaluation of the mortars for their application in construction.

Table 1. Materials Used.

Materials	Origin
Fine Aggregate	Tanlahua Quarry (Blue Dust)
Cement	Portland Pozzolanic Type HS
Water	Metropolitan District of Quito Network (EPMAPS)
Graphene Nanoparticles	XFNANO

3.1. Portland Cement

Ordinary Portland cement is widely used in various applications within the construction industry. In this study, Portland Pozzolanic Cement Type HS was used, which complies with the requirements of NTE 2380 and ASTM C1157.

3.2. Fine Aggregate

Fine aggregate refers to inert material particles capable of passing through a sieve with a 4.75 mm mesh. This type of material is widely used in the preparation of concrete and mortar to enhance the physical properties of these materials. The material used for experimental work was obtained locally, complying with the specifications of NTE INEN 2536:2010 and NTE INEN 0696:2011, which detail the granulometric ranges. The properties of the fine aggregate are presented in Table 2 and Figure 2.

Table 2. Aggregate Properties.

Characteristics	Unit	Results
Specific Gravity	g/cm^3	2.92
Water Absorption	%	2.40
Fineness modulus		2.29

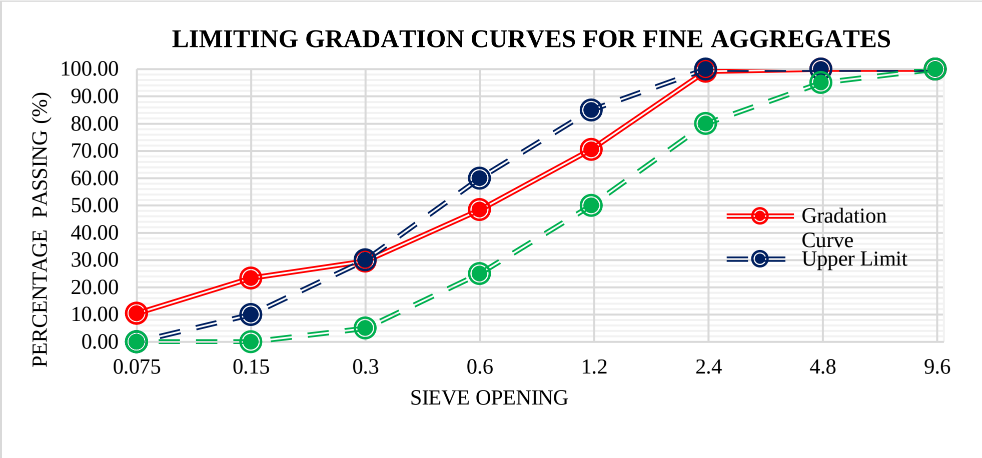

Figure 2. Granular distribution of used fine aggregate.

3.3. Water

Water plays a crucial role in concrete by participating in chemical reactions with cement. It is essential that the water used be potable, domestic, clean, and free from any harmful substances.

3.4. Graphene Nanoparticles

In the current context, acquiring graphene nanoparticles in Ecuador faces certain limitations, primarily associated with the challenges inherent in their manufacture and the time required for their synthesis through chemical processes. Given these constraints, the decision was made to import this material from China, specifically from Nanjing, through Jiangsu XFNANO Materials Tech, one of the leading companies in large-scale graphene synthesis.

The imported graphene is presented in the form of carbon nanotubes, a format that stands out for its nature as a fine, lightweight gray powder. For this project, a quantity of 1 kilogram of this material has been acquired. The choice of this specific type of graphene responds to its properties and applicability in our research and development objectives.

3.4.1. Validation of Graphene Nanoparticles through Laboratory Tests

To ensure the quality and properties of the imported nanomaterial, exhaustive laboratory tests have been carried out, including Energy Dispersive Spectroscopy (EDS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD), which have allowed for a detailed characterization of the nanomaterial, providing valuable information on its structure, composition, and physicochemical properties.

3.4.2. Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) Tests

The EDS test, combined with the SEM test, allows for the analysis of the chemical composition of a sample by detecting the X-rays emitted by atoms when excited by an electron beam. This provides data on the chemical elements and their proportion in the sample, facilitating the obtaining of detailed images of the topography and morphology of materials, revealing the shape and texture of objects at micro and nanometric scales.

The EDS and SEM tests detail the material composition, demonstrating the effectiveness of the extracted graphene. This shows a composition of **93.979%** pure carbon and **5.836%** oxygen, as shown in Figure 3. Additionally, in Figure 4. (a) - (b) - (c) - (d), detailed images illustrate the topography and morphology of graphene at micrometric scales of 50, 10, 5, and 1 μm, showing a structure of thin layers with partially folded edges, confirming the effectiveness of graphene extraction. These images also allow for an appreciation of the specific texture of the material. The results are consistent and validate the graphs provided by the XFNANO company as shown in Annex 1, although at a different scale, but with the same shape and texture of graphene.

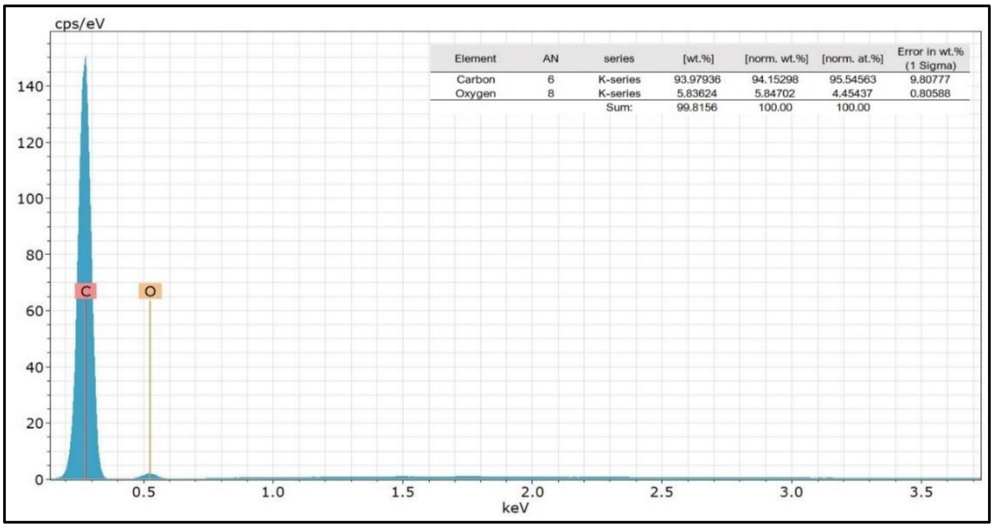

Figure 3. Graphene composition.

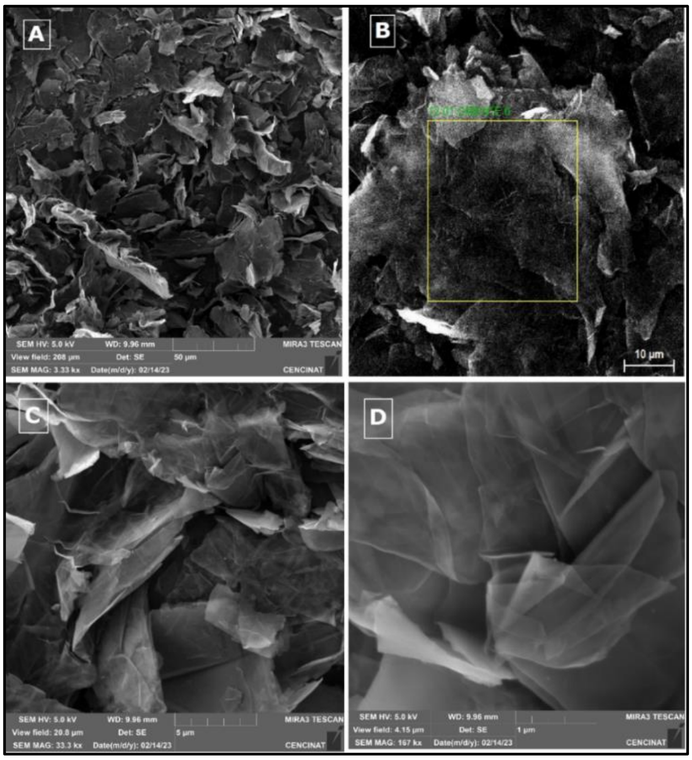

Figure 4. Morphology and topography of graphene nanoparticles.

Transmission Electron Microscopy (TEM) Test

Through the TEM test, the atomic-level characteristics and structural properties of graphene are analyzed. The high resolution of this test allows for the visualization of the hexagonal arrangement of carbon atoms in graphene, at a nanometric scale as shown in Figure 5 (a) - (b) - (c) - (d), thus identifying the monolayer of graphite (Graphene) at scales of 100, 200, and 500 nm, and detecting possible defects and impurities in its structure. These details are crucial, as any alteration in its structure can modify its electronic, mechanical, and optical properties. The TEM test offers a deep perspective of the crystalline structure of graphene, and its quality and purity. It is worth mentioning that these results are validated with the graphs supplied by the XFNANO company (Annex 2).

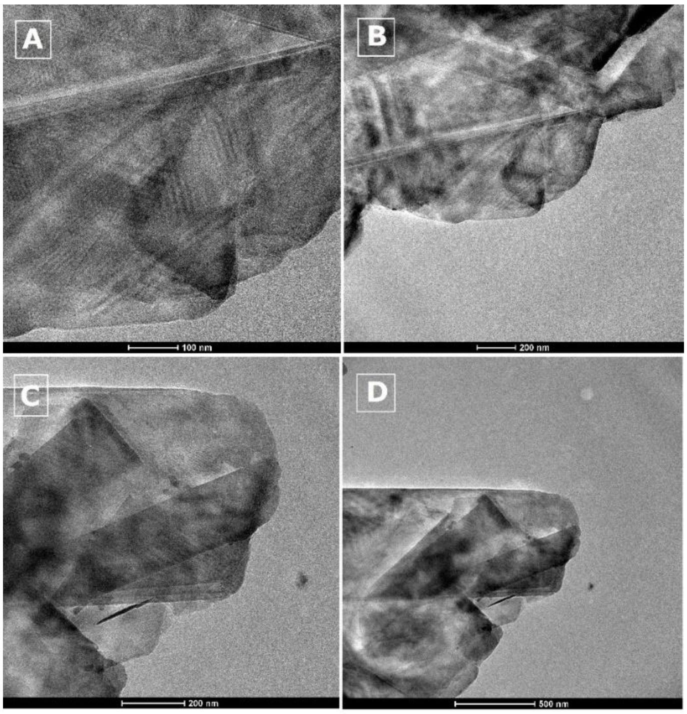

Figure 5. nanometric composition of Graphene.

X-Ray Diffraction (XRD) Test

The analysis using X-Ray Diffraction was conducted to evaluate the crystalline phase of the material, evidenced in the X-Ray Diffraction Test (XRD). By contrasting these results with those obtained by the XFNANO company, its composition was corroborated. The test was carried out in a diffractometer using a scanning range of 0 to 90° on the 2θ scale, at a speed of 0.02 degrees per second. As shown in Figure 6, notable peaks observed near the angles 2θ = 26.41 [°], 43.24 [°], and 54.48 [°], linked to the reflective planes (45399.39), (792.02), and (2169.77). These peaks confirm the existence of graphene in its crystalline phase and differentiate a monolayer laminar structure (Annex 3).

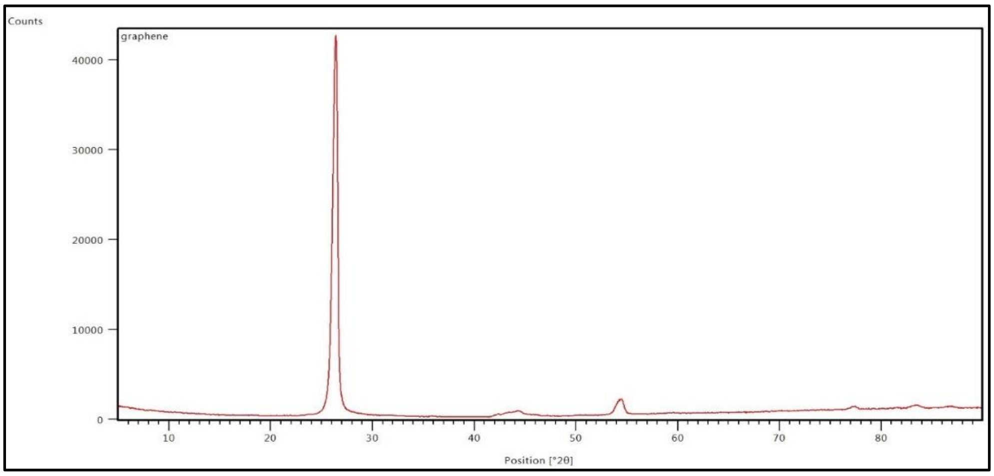

Figure 6. Composition of a graphene monolayer.

3.5. Design Methodology

In the study presented, a detailed experimental design methodology was adopted from the book "The Technology of Mortars" by Rodrigo Salamanca (Salamanca, 2001). This methodology is characterized by its systematic and chronological approach in the development of mortars that meet pre-established strength specifications. The process involves the precise determination of the proportions of the different materials used, as detailed in Table 3. These specific proportions are essential for the proper preparation of test specimens, which are fundamental in the design and evaluation stages of the mortar, thus ensuring the accuracy and reliability of the results obtained.

Table 3. Quantity of material for 1m^3.

Mix Name	W/C Ratio	Cement	Fine Aggregate	Water	Graphene
		kg	kg	kg	kg
M	0.78	373.00	1489.82	290.94	-
M+G$_{0.25\%}$	0.78	372.07	1489.82	290.94	0.93
M+G$_{0.50\%}$	0.78	371.14	1489.82	290.94	1.87
M+G$_{0.75\%}$	0.78	370.20	1489.82	290.94	2.80
M+G$_{1.00\%}$	0.78	369.27	1489.82	290.94	3.73

M: Standard mortar mix with zero percentage of graphene nanoparticles.

M+G0.25%: Standard mortar mix with 0.25 percent graphene nanoparticles.

M+G0.50%: Standard mortar mix with 0.50 percent graphene nanoparticles.

M+G0.75%: Standard mortar mix with 0.75 percent graphene nanoparticles.

M+G1.00%: Standard mortar mix with 1.00 percent graphene nanoparticles.

The mortar mixes were designed keeping the water/cement ratio constant, however, depending on the percentages of graphene nanoparticles relative to the weight of the cement, this material has been included, reducing the amount of graphene to be used. The quantity of the different materials required for 1m^3 are detailed in the Table 4. For the case study, the design methodology employed allows obtaining a mortar that satisfies a desired resistance, through a chronological order of steps, for which the different quantities of materials have been determined as detailed in Table 4.

Regarding the prefabricated mortars, with defined quantities according to the requirements, it was decided to maintain the water/cement ratio and use the amount of prefabricated material according to the specifications.

3.6. Mortar Mix Tests

The tests to which the different prepared specimens were subjected are simple compression test and adhesion strength test. For the simple compression test, it is necessary to calculate the volume of material needed for 50mm edge cubes. For the adhesion test, it is necessary to calculate the volume of material required to determine the filling on a 20x40cm block with a thickness of 1cm coating. Tables 4 and 5 detail the number of specimens prepared to perform the different tests.

Table 4. Number of specimens for simple compression testing.

No.	Mix Name	Description	Test	Number of specimens
1	M	Standard Mix	Simple Compressive Strength	12
2	M+G$_{0.25\%}$	Standard Mix + 0.25% Graphene Nanoparticles		12
3	M+G$_{0.50\%}$	Standard Mix + 0.50% Graphene Nanoparticles		12
4	M+G$_{0.75\%}$	Standard Mix + 0.75% Graphene Nanoparticles		12
5	M+G$_{1.00\%}$	Standard Mix + 1.00% Graphene Nanoparticles		12
6	M. Pref 1	Prefabricated Mortar Type 1		12
7	M. Pref 2	Prefabricated Mortar Type 2		12
		Total		84

Table 5. Number of specimens for adhesion test.

No.	Mix Name	Description	Test	Number of specimens
1	M	Standard Mix	Adhesion Strength	1
2	M+G$_{0.25\%}$	Standard Mix + 0.25% Graphene Nanoparticles		1
3	M+G$_{0.50\%}$	Standard Mix + 0.50% Graphene Nanoparticles		1
4	M+G$_{0.75\%}$	Standard Mix + 0.75% Graphene Nanoparticles		1
5	M+G$_{1.00\%}$	Standard Mix + 1.00% Graphene Nanoparticles		1
6	M. Pref 1	Prefabricated Mortar Type 1		1
7	M. Pref 2	Prefabricated Mortar Type 2		1
		Total		7

4. Results and Discussion

4.1. Simple Compressive Strength

Compressive strength is a crucial factor determining the ability of structures to withstand loads and deformations in the construction sector. The results presented in Table 6 summarize the strengths obtained at different ages of various types of mixes prepared.

Table 6. Summary of simple compressive strength of mortars.

Mix Name	24 hours	3 days	7 days	28 days
	MPa	MPa	MPa	MPa
M	3.73	7.77	9.91	15.4
M. Pref 1	1.96	3.72	6.27	13.08
M. Pref 2	2.22	4.71	7.76	13.05
M+G$_{0.25\%}$	3.72	9.05	10.21	17.4
M+G$_{0.50\%}$	3.61	9.01	10.78	14.63
M+G$_{0.75\%}$	3.39	8.62	10.36	13.79
M+G$_{1.00\%}$	3.31	8.09	10.03	13.74

It is observed that the compressive strengths obtained at 28 days of the different types of mixes prepared exceed the resistance limit established in the NTE INEN 2 518 standard of 12.4 MPa, indicating that they can be used in construction without issues. By adjusting the design methodology, the standard mix reaches a strength of 15.40 MPa, representing a 24% increase compared to what is stipulated in the regulations. On the other hand, prefabricated mortars 1 and 2 exceed the specified strength by 5%.

In the case of mixes prepared with graphene nanoparticles, notable variations in strength are observed compared to the standard. The mix using 0.25% graphene exceeds the specified strength in the standard by 40% and is 13% higher than the standard mix. However, varying the amount of graphene nanoparticles, the strengths fluctuate. Mixes with 0.75% and 1.00% graphene increase their strength by 11% relative to the standard but decrease by 11% compared to the standard mix. In contrast, the mix with 0.50% graphene nanoparticles increases its strength by 18% compared to the standard but decreases by 6% compared to the strength of the standard mix.

It is important to highlight that among the intrinsic properties of mortars, one of the most notable is the progressive increase of their strength over time.

4.2. Simple Compressive Strength vs Time

Figure 7 shows the variation of strength over time, representing the age of the tests performed at 24 hours, 3 days, 7 days, and 28 days of the different types of mixes.

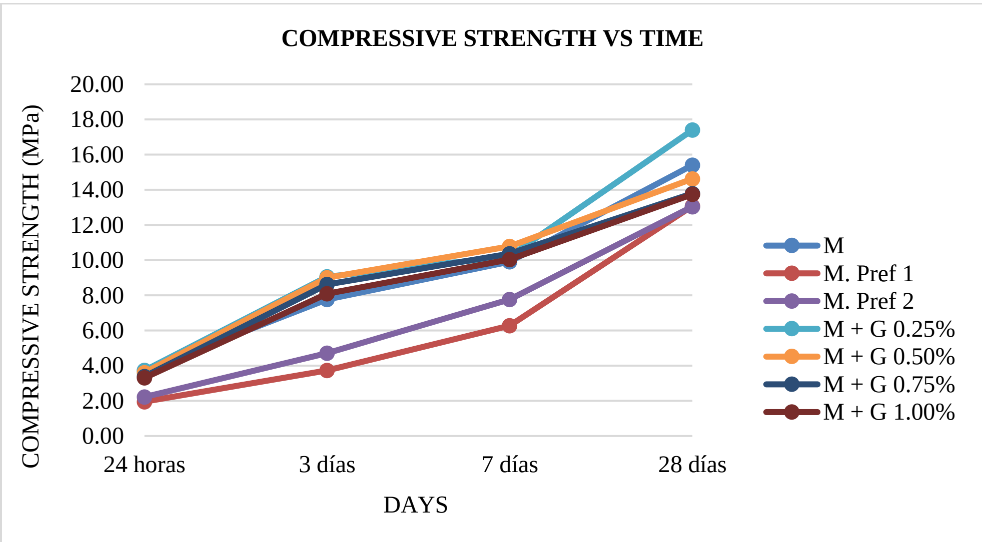

Figure 7. Simple Compressive Strength vs Time.

In general, prefabricated mortars 1 and 2 show the lowest strengths achieved at different ages. Within these types of mixes, prefabricated mortar 1 exhibits the least strength, possibly due to the amount of water used. Compared to prefabricated mortar 2, which uses 0.45L of water per 2kg of mix, prefabricated mortar 1 employs a greater quantity of water per 2kg of mix. It should be noted that the water/cement ratio is inversely proportional to strength, meaning the lesser the water in the mix, the greater the strength.

As observed in Figure 8, among the various types of mixes prepared, the one containing 0.25% graphene nanoparticles achieves the highest strength at 28 days.

Figure 8 displays the progression of strength of different mortar mixes over time. After 24 hours, both the standard mix mortar and those with 0.25% and 0.50% graphene nanoparticles show similar strengths. However, after 3 days, only the mixes with graphene nanoparticles maintain comparable strengths, surpassing the standard mix.

After 7 days, it is evident that the mix with 1.00% graphene nanoparticles surpasses the strength of the mix with 0.25% graphene nanoparticles by 5% and the standard mix by 9%. However, at 28 days, the mix with 0.25% graphene nanoparticles stands out by achieving the highest strength among all mixes, surpassing the mortar with 0.50% graphene nanoparticles by 26% and the standard mix by 13%.

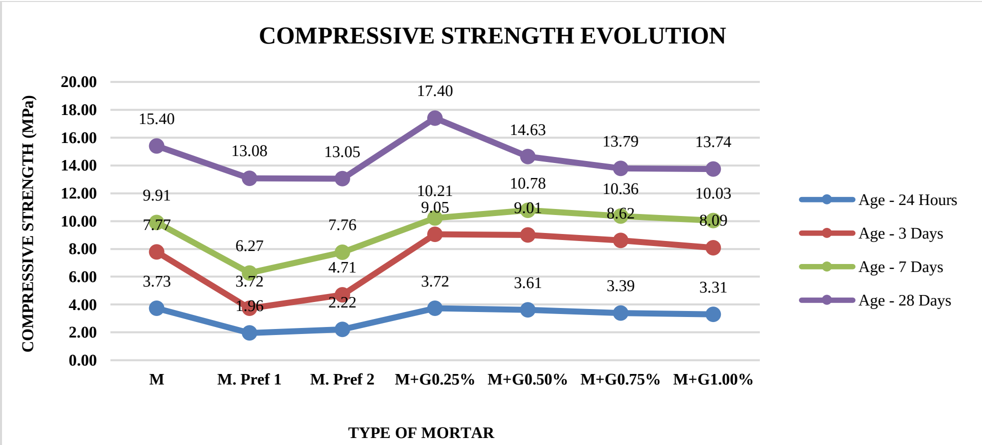

Figure 8. Evolution of Simple Compressive Strength.

4.3. Adhesion Strength

The ability of mortars to adhere is crucial in structures, as good adhesion prevents detachment or collapse of the plaster, which could impact the wall's integrity and cause damage or injuries.

Using the test methodology of the UNE-EN 1015-12 standard, Table 7 shows the results of the arithmetic average of 5 specimens tested at 28 days.

Table 7. Summary of bond strength of mortars.

Mix Name	28 days
	MPa
M	0.72
M. Pref 1	0.31
M. Pref 2	0.2
M+G$_{0.25\%}$	1.03
M+G$_{0.50\%}$	0.58
M+G$_{0.75\%}$	0.42
M+G$_{1.00\%}$	0.24

In this table, it can be observed that the standard mortar meets the minimum adhesion strength established in the NTE INEN 2 615 standard, which specifies a minimum strength of 0.70 MPa at 28 days. The standard mortar achieves a strength of 0.72 MPa, slightly exceeding the minimum required, making it suitable for construction activities. On the other hand, the inclusion of 0.25% graphene nanoparticles relative to the weight of cement significantly increases adhesion strength, reaching a value of 1.03 MPa. This strength is 46% higher compared to the standard mix.

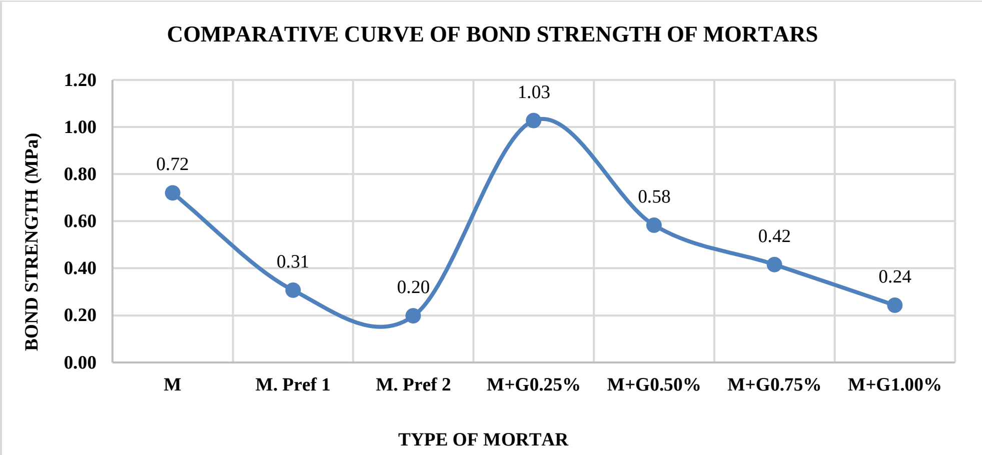

Figure 9. Bond strength of mortars.

The consolidated technical analysis of the results obtained from the prefabricated mortars and mortars with more than 0.25% graphene nanoparticles indicates a complex interaction between the concentration of graphene and the mortar's mechanical and adhesive properties. On one hand, the presence of graphene, despite its recognized mechanical and thermal properties, fails to meet the minimum adhesion standards set by national regulations when the concentration exceeds 0.25%. This phenomenon suggests a possible imbalance in the mortar composition, negatively affecting its adhesive properties.

On the other hand, mixes containing 0.25% graphene nanoparticles demonstrate superior adhesion compared to other combinations and prefabricated mortars, as evidenced in Figure 9. This implies that while graphene nanoparticles can enhance certain mechanical properties of the mortar, their use in high concentrations may be counterproductive in terms of adhesion, a crucial factor for the material's structural performance. Similarly, in the realm of prefabricated mortars, it has been observed that the experimented dosages resulted in notably low strengths. This phenomenon seriously jeopardizes the mortar's ability to achieve adequate adhesion strength, a critical aspect to ensure its efficacy and durability in practical applications.

5. Conclusions

- The analysis of aggregates, including blue rock powder and HS type cement, allowed for adjusting a mix with proper flow and manageable properties, which not only meets but exceeds the INEN 2 518 standards in terms of strength and adhesion. This mix served as the basis for developing various dosages, incorporating different percentages of graphene, and comparing them with prefabricated and conventional mortars.
- Through advanced techniques such as EDS, SEM, TEM, and XRD, a detailed understanding of the nature and quality of graphene was achieved, revealing a laminar structure of pure carbon with minimal impurities and a clearly defined crystalline phase. These results reliably validate the information provided by XFNANO, ensuring that the graphene nanoparticles used possess the appropriate properties and characteristics for their application in mortars.
- It was established that the optimal range for incorporating graphene nanoparticles in mortars is up to 0.25% of the weight of cement. Beyond this percentage, a decrease in key

properties such as compressive strength, adhesion, workability, and consistency was observed, attributed to the agglomeration of nanoparticles and their interference in cement hydration.

- The inclusion of graphene nanoparticles in mortars significantly improves compressive strength and adhesion, surpassing prefabricated and conventional mortars. However, current design methodologies do not guarantee a specific final strength, making it necessary to control the water/cement ratio and supervise materials to maximize the benefits of graphene.
- Both the standard mortar and the mortar with 0.25% graphene nanoparticles exceeded the adhesion strength required by the standards, with the graphene mortar standing out for its higher strength compared to the standard. This phenomenon indicates that there is an optimal point in the proportion of graphene that should be investigated further. Future research should focus on adjusting the amount of graphene nanoparticles within mortars to achieve a balance that not only meets regulatory standards but also maximizes the enhanced properties that graphene can offer in the field of construction.

Declaration of conflicting interests

The authors declare that they have no competing financial interests or personal relationships that could have influenced the information presented in this article.

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Annex 1 SEM (Scanning Electron Microscope) test provided by XFNANO.

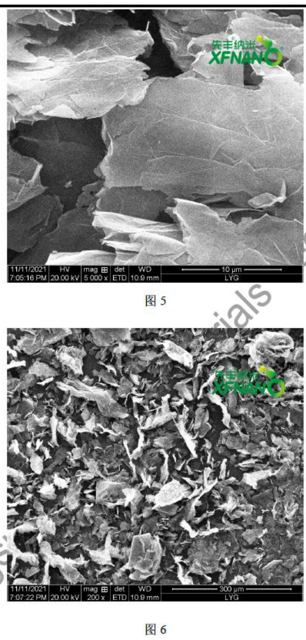

图 5,6 工业级薄层石墨烯纳米片扫描电镜图

Annex 2 TEM (Transmission Electron Microscopy) test by the company XFNANO.

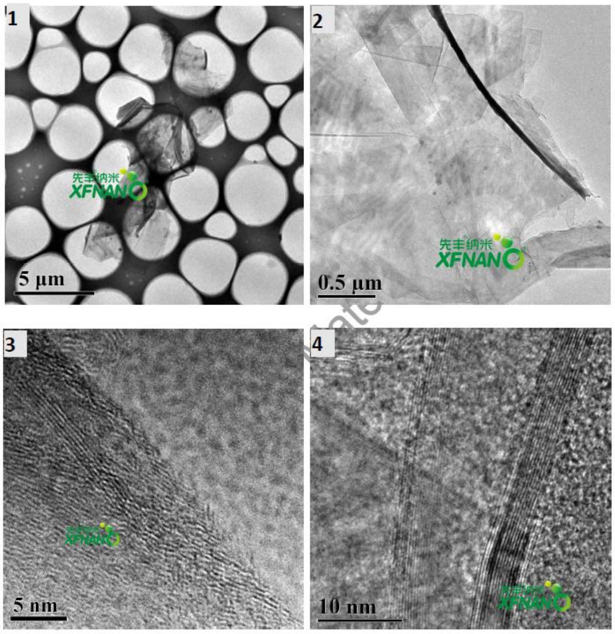

图 1-4 工业级薄层石墨烯纳米片透射电镜图

Annex 3 XRD (X-ray diffraction) test by the company XFNANO.

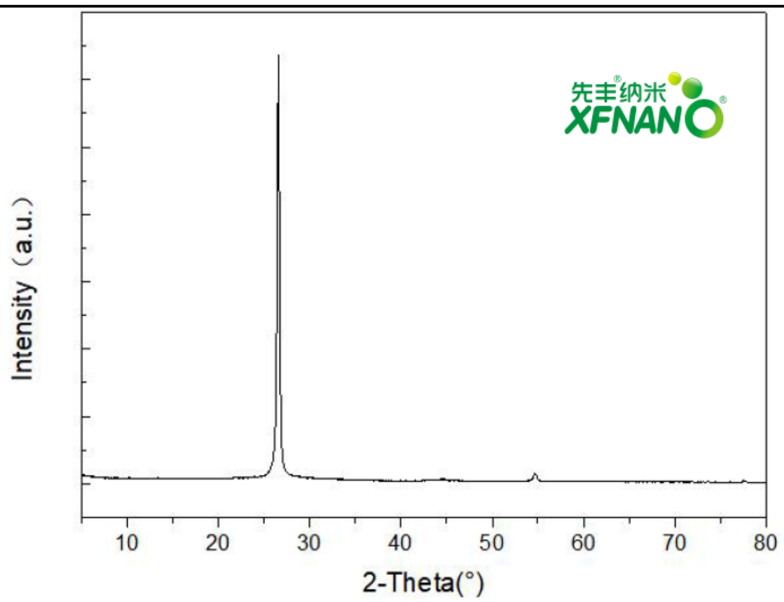

图 8 工业级薄层石墨烯纳米片 X-射线衍射图