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Journal of Architecture and Design

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Knowledge Area

The works must be unpublished and refer to issues of international architecture, technological innovation in architecture, industrial design, business design techniques, multimedia design, advertising design, web system design, residential architecture and other topics related to Engineering Sciences and Technology.

Presentation of the Content

In Issue 20, is presented an article *Temple of the Assumption of Our Lady of Tochimilco, Puebla, Mexico, a convent complex belonging to the 16th-century convent route*, by Morales-Ortega Alejandro, Vázquez-Torres María del Rayo and Navarrete-García Mónica, with adscription at Benemérita Universidad Autónoma de Puebla, in the next article we present, *Static and dynamic seismic analysis for the construction of structural concrete portal frames in Manzanillo, Colima* by Caro-Becerra, Juan Luis, Martínez-Hernández, Wilfrido, Mayoral-Ruiz, Pedro Alonso and Hernández-Magdaleno, Alfonso Manuel, with adscription at Universidad Politécnica de la Zona Metropolitana de Guadalajara and Universidad de Guadalajara, in the next article we present, *Mechanical behavior of sustainable concrete; case study of low substitutions of fine plastic as aggregate* by Arias-Ortiz, Jhovanny, Gutiérrez-Moreno, Manuel, Arcos-Vega, José Luis and Calderón-Ramírez, Julio, with adscription at Universidad Autónoma de Baja California, in the next article we present, *Digital reconstruction of historical monuments with drones and 3D Photogrammetry: An ICT application for heritage management* by Vega-Flores, María Yaneth, Téllez-Martínez, Jorge Sergio, Sánchez-Hernández, Miriam Zulma and Fernández-Flores, Víctor Delfino, with adscription at Instituto Tecnológico de Morelia, in the last article we present, *Development and application of a natural waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica] in sustainable restoration materials for the conservation of built heritage [vernacular architecture]: case study of the Mezquital Valley, Hidalgo* by Rodríguez-Uribe, Juan Carlos, Trejo-Torres, Zaira Betzabeth, Benavides-Rosales, Antonio and Benítez-Alonso, Margarita, with adscription at Tecnológico Nacional de México - Instituto Tecnológico Superior de Huichapan and Secretaria de gestión integral de riesgos y protección civil.

Content

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Article

Temple of the Assumption of Our Lady of Tochimilco, Puebla, Mexico, a convent complex belonging to the 16th-century convent route

Templo de la Asunción de Nuestra Señora de Tochimilco, Puebla, México, conjunto conventual perteneciente a la ruta de los conventos del siglo XVI

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Abstract

The contribution of this research is that it rescues the work of researchers who have disseminated the importance of preserving this convent complex, designated a World Heritage Site since 1999. This complex is part of the Route of the 16th-century Monasteries, attracting tourism to a community with a high degree of economic vulnerability that survives primarily on agriculture and tourism. Furthermore, the convent complex is one of the meeting places that allows for community cohesion and the preservation of its cultural identity. Therefore, disseminating its existence can benefit a community and preserve this heritage. The discussion is divided into three parts: The first establishes the importance of the location of the convent complex; the second outlines the concepts that influenced its construction; and the third describes the most relevant components of the complex.

INVESTIGACIÓN		
Objetivos	**Metodología**	**Contribución**
Identifica elementos clave representativos del templo mediante investigación	Análisis: diagnóstico, programa, problema, forma, diseño, calidad y materialización.	Divulgación pública de información en difusión del conocimiento.

Trade route, architecture, and components

Area: Advocacy and attention to national problems

Resumen

La contribución de esta investigación, es que rescata trabajos de investigadores que han divulgado la importancia de la conservación de este conjunto conventual denominado como patrimonio de la humanidad desde 1999. Este conjunto pertenece a la Ruta de los monasterios del siglo XVI, atrae al turismo hacia una comunidad con un alto grado de vulnerabilidad económica que sobrevive principalmente, de la agricultura y el turismo. Además, el conjunto conventual es uno de los centros de reunión que permiten la cohesión de la comunidad y la conservación de su identidad cultural. Por ello, si se divulga su existencia, se podrá favorecer a una comunidad y se preservará este patrimonio. En la discusión, se forma por 3 partes: En la primera, se establece la importancia de la ubicación del conjunto conventual; en la segunda, se manifiestan los conceptos que influyeron en su construcción y en la tercera se describen los componentes del conjunto, más relevantes.

INVESTIGATION		
Objetivos	**Metodología**	**Contribución**
Identify key representative elements of the temple through researh.	Analysis, diagnosis, program, problema, form, design, quality and materialization.	Public dissemination of information in the diffusion of knowledge.

Ruta comercial, arquitectura y componentes

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Introduction

The conquest of Mexico by expansionist Spain first resulted in a process of subjugation and hybridisation that sought to impose a single identity on the Americas. Subsequently, it led to a lack of understanding of the ways of life of each community, which, despite belonging to the same region, had diverse ways of thinking and acting [Montes de Oca, 2001].

The conquest of Tenochtitlán in 1521 marked the beginning of the construction of what is now Mexico, and was a unique experience at that time, both for the Spanish and for the natives. The armed conflict gave way to cultural and religious confrontation [Artigas, 1999]. The conquest of Mexico is considered a model conquest due to the way it was carried out. It was overwhelming, allowing for a change in ideology of the dominant force in the face of well-organised and defined cultures [Zanetti and Manzoni, 2022].

Between 1523 and 1572, religious orders were tasked with carrying out 'the spiritual conquest of Mexico' or 'the first evangelisation', which allowed the Spanish to control the territory and its population... This evangelisation was of fundamental importance, and although it was largely incomplete and somewhat syncretic, it allowed Spanish rule to be established through the ideological unity of a common religion of the rulers and the ruled [Martínez and Santos, 2015, p. 244].

It should be noted that the concept of syncretism is an expression used in cultural anthropology and theology as a term that attempts to describe in a single word the struggle between two forces that seek to survive, a process in which cultural hybridisation manifests itself. This is what Villalobos [2006] calls 'co-participation of cultural forms,' since coexistence generates mixtures that translate into new forms of behaviour, art, rituals, culture, identity, or architecture, among other areas.

Subsequently, the struggle between two powers gives way to a period of imbalance of forces, in which both sides seek benefits. However, syncretism is not always peaceful, as it is common for the dominant side to impose its ideas or a new order, turning those ideas into a transferable cultural product.

Syncretism or reinterpretation occurs through the confrontation between the two cultural concepts that try to "adjust" and are partially transformed, moving away from the rigorous concept of acculturation and cultural miscegenation [Gussinyer, 1996] ..." There is diverse evidence of religious syncretism, ranging from artistic expressions still preserved in the country's various convent complexes to the religious festivals, prayers, attire, and celebrations that are still practised today [Montes de Oca, 2001, p. 47].

In the case of architecture, intense contradictions arise as a result of the impositions of the dominant culture, and in being subject to this, it displays extraordinary originality. In the case of the Mesoamerican cultures dominated by the conquistadors, an architecture developed that incorporates some pre-Hispanic architectural aspects [Gussinyer, 1996].

Methodology

The research method involved developing exploratory processes in the community since 2015 to understand the conditions of the space and the community. To this end, qualitative methods were used to disseminate the need for cultural heritage conservation.

Qualitative research is flexible and follows guiding principles. It is an empirical research process on the characteristics of the object of study and its context [Quecedo and Castaño, 2002]. Therefore, the research was carried out by reviewing and analysing documentary sources, visiting the site, and interviewing specialists in the areas of heritage structures and conservation, as well as the inhabitants of the municipalities of Tochimilco.

Results

The authors of this article began visiting Tochimilco in 2015, and one of the sites they visited was the Temple of the Assumption of Our Lady. During the process, conversations were established with the population, where the traditions and customs of the place could be learned and appreciated.

Sunday mass became an activity where the population gathered to worship Christ. Afterwards, in the atrium, they talked and agreed on their work and family activities, and organised committees for the maintenance of the temple and the festivities.

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Some of the religious festivals include the Feast of the Assumption, which is celebrated on 15 August in the parish of the former convent of the Assumption of Our Lady, and the festival of the indigenous people of the saints or Day of the Dead, celebrated on 1 and 2 November, to give thanks to them for the harvests. After the 2017 earthquake, this community practice was suspended due to the damage caused by the earthquake. Residents of Tochimilco helped to clear the rubble and clean up the spaces, safeguarding furniture, images, and some fractured architectural elements. In addition, scaffolding was erected to support the arches of the convent.

The temple remained open during the first few weeks, but when the National Institute of Anthropology and History [INAH] decided to intervene in the building, it was closed to the public. In 2018, the INAH carried out non-invasive studies with ground-penetrating radar to obtain results on the composition and dimensions of the foundations and walls, as well as fractures in the walls. The damaged elements were the retaining walls, battlements, temple vaults, walls, and subsidence and cracks in the floor.

This allowed the discovery of a mass of water in the subsoil of the temple, which is unknown whether it is natural or artificial, which dampens the walls and may endanger the building. In 2018, a meeting was held with representatives of the INHA, with support from the United Nations Educational, Scientific and Cultural Organisation [UNESCO], Seguro Banorte and the Mexican Natural Disaster Fund [FONDEN], as well as representatives of companies specialising in scaffolding and shoring, using the results of the ground-penetrating radar. This work was halted by the Covid-19 pandemic and restoration work resumed in 2020. The work was slow, as it was considered that there were more damaged temples that needed to be repaired more urgently. The official opening of the temple was set for 13 August 2025, in preparation for the feast of Our Lady of the Assumption on 15 August.

The route of the monasteries

A trade route is a road where different types of goods circulate. Trade is an activity involving the exchange of goods, for which patterns of behaviour are established, creating networks or routes that subsequently form complex networks.

Trade networks cover large territories, allowing the formation of empires that control trade relations, such as the Aztec Empire. In pre-Hispanic Mesoamerica, a regional system was formed, composed of units that behaved independently and interacted with each other. In these commercial processes, not only are goods and resources exchanged, but moments of cultural and technological hybridisation also occur [Cossens, 2019].

The natives lived scattered across large areas [nuclear families], so the Spanish concentrated the populations into communities, grouping together dispersed families to 'live under police supervision'; that is, monitored, controlled, and indoctrinated in the Catholic faith.

The territory was divided by religious orders as follows: Franciscans [Mexico, Tlaxcala, Texcoco, Huejotzingo, Cuernavaca, Calpan, Huaquechula, and Tochimilco]; Dominicans [Oaxtepec, Tepoztlán, Tetela del Volcán and San Andrés Hueyapa] and Augustinians [Ocuituco, Totolapan, Yecapixtla, Tlayacapan, Atlatlahucan and Zacualpan de Amilpas]. It can be said that evangelisation was not only aimed at indoctrination, but also at territorial expansion [Artigas, 1999].

At first, the Spanish used the same trade routes that existed in Mesoamerica to take advantage of their organisation and control. Spanish convents and pre-Hispanic temples have in common that they were related to trade and its routes.

For this reason, the buildings along the trade routes had similar characteristics, despite belonging to different religious orders [Martínez and Santos, 2015].

The first monasteries of the 16th century form what is now known as the route of the convents between Morelos and Puebla, comprising 14 monasteries recognised by UNESCO as World Heritage Sites on 17 December 1994... three in the state of Puebla [San Miguel in Huejotzingo, San Andrés in Calpan and San Francisco in Tochimilco] and 11 in the state of Morelos" [Sánchez, 2013, p. 213].

The convents were located in already populated areas with intense trade, which allowed for control of the territory and its inhabitants.

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For this reason, evangelisation and symbols of power had to be established to ensure the stability of New Spain [Martínez and Santos, 2015].

The highest points in each region were sought for the construction of the monasteries, as in the case of the slopes of the Popocatépetl volcano. In Puebla, Santiago Xalitzintla is the closest town to the volcano, at a distance of 12 km; Santa Cruz Cuautomatitla and Tochimilco are 12 km away; Huejotzingo is 46 km away; and Calpan is 12 km away. In the state of Morelos: Cuernavaca 60 km; Tepoztlán 91 km; Oaxtepec 81 km; Tlayacapan 89 km; Yecapixtla 18 km; Ocuituco; Tetela del Volcán 18.2 km; Hueyapan 15 km; Zacualpan de Amilpas 18 km. Approximately.

Almost all the towns where the convents of the mendicant orders of the 'route' were built on the slopes of Popocatépetl were hubs on the regional trade routes and to the lake ports of the Altiplano lakes, but divided into two circuits: one located in the state of Morelos and the other in the state of Puebla [Martínez and Santos, 2015, p. 260].

In addition, the roads and routes represented growing economic development, which changed in line with that progress and became a system of spatial, economic and political organisation [Martínez and Santos, 2015]..." The medieval mass of convents in the middle of villages such as Tlayacapan established an architectural symbolism of power, hence the urgency to build them in the purest European style, without any trace of the pre-Hispanic era [Martínez and Santos, 2015, p. 244].

Architecture

Spanish religious architecture had a structured and mature design, although in Mexico some elements of the conquered population were allowed to be incorporated into the architecture.

Pre-Hispanic influence was not observed, so one cannot speak of architectural eclecticism [Martínez and Santos, 2015].

Religious sites in Mexico emerged with a fundamental contradiction: the Spanish used covered spaces to impart Christian liturgy, while Mesoamerican culture used open spaces to worship their gods.

These two visions of religious space were applied in the development of new constructions in 16th-century Mexico.

There are different approaches to reinterpreting the religious space of the two worlds, which favoured evangelisation, as it took place rapidly and was less traumatic. However, the influence of pre-Columbian culture on architecture gradually disappeared and was reduced to the application of simple construction techniques and materials and elements in architectural decoration, resurfacing at the end of the 17th century and in the 18th century in viceregal Baroque architecture [Gussinyer, 1996].

The architecture created by the evangelising orders had homogeneous results, that is, similar models of architectural and construction design were used, with differences from European buildings.

As already mentioned, pre-Hispanic communities were located at distant points from each other, and the Spanish concentrated these communities in urban centres for their control.

For this reason, the articulation of the conventual atrium and plaza was very important for the inhabitants, as it united the civic and religious spheres.

Although this relationship existed in Europe and other regions of the world, the atrium and plaza were included in the architectural programme in New Spain to meet the need to group large populations together and to create similarities between pre-Hispanic and Christian religious rituals. Therefore, pre-Hispanic ceremonial centres were revived in the architectural programme of religious centres in New Spain [Reyes, 2016].

As already mentioned, the creation of a new concept of 'Nation' brought with it new circumstances and needs to be resolved, which is why architectural programmes and their solutions were different from what had been established. An example of this is the Catholic ritual that was performed in open spaces in relation to the natural landscape, which became a 'sacred open-air enclosure.'

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This was developed through platforms, retaining walls, buildings on ceremonial centres, among other architectural elements of pre-Hispanic origin. On the other hand, buildings were erected at visually significant points to increase their importance within the context. For this reason, psychological reference points from the ancient sites were used, ahead of the concept of spatial continuity, together with atriums. In addition, this concept accelerated the process of evangelisation, as built spaces were not required [Artigas, 1999].

It should be noted that some authors consider the open chapel or 'Indian chapel' and the atrium to be a pre-Hispanic innovation. However, other authors believe that these were the result of the early stages of evangelisation and even that their origin is European in the medieval and Muslim periods, although this is still controversial [García, 2015].

At the same time, they resorted to forms of settlement that were opposed to those traditionally found in the pre-Columbian rural world, but which were nevertheless present in their land in some way. The first section deals with atriums, an ancient early Christian tradition rarely used in late medieval European architecture [Gussinyer, J. 1996, p. 213].

For all the above reasons, it can be said that, although the atrium was known in Europe, at the time of the conquest it was not part of the Spanish architectural programme.

Therefore, there is controversy as to whether the origin of the atrium is European or pre-Hispanic; however, it can be considered that although the atrium was used in Europe, at the time of the establishment of religious complexes in what is now Mexico, it was not part of the architectural programme. Its introduction was the result of the need to evangelise a large number of people, and as there was no building to do so, evangelisation took place in open spaces, which was a pre-Hispanic custom and a functional necessity.

The founding of convents in the Spanish overseas territories could take ten, fifteen or even twenty years, or the negotiations could never be concluded and the project would remain only a pile of correspondence [Zavala, 2025, 164].

With the construction of these buildings, completed just a few decades after the fall of Tenochtitlán, unknown concepts emerged: large atriums, 'posa chapels,' orchards, open chapels, among others, considered the most important American contribution to Western architectural culture [García and Gómez, 2023] ..." The posa chapels, the open chapels, and even the atrium crosses, etc., stand out. These are themes of American origin, despite the fact that there is often a desire to invalidate any initiative with Amerindian roots" [Gussinyer, 1996, p. 214].

Components of the].

Components of the temple

The Temple and former convent of La Asunción de Nuestra Señora in Tochimilco, founded in 1560 by Fray Diego de Olarte, is one of the first monasteries of the 16th century [Ortiz, 2013].

The convent complex is located on the slopes of the Popocatépetl volcano, and these buildings are listed by UNESCO as World Heritage Sites..." These are very unique villages whose origins date back to pre-Hispanic times and where the characteristic dwellings have been made of earth since before the establishment of the convents that led to the declaration [Guerrero, 2008, p. 112].

The Temple and former convent of La Asunción de Nuestra Señora is one of the buildings recognised for its condition and its unique architectural style, designed for evangelisation and as a place where there was a significant exchange of influences between European and American cultures... "It is a typical example of 16th-century fortress architecture. It has an open chapel, tower and belfry. Antonio de Ciudad Real wrote: 'The convent is finished, with its church, upper and lower cloisters, dormitories and cells, and vegetable garden' [Vergara and Jackson, 2022, p. 337].

At the time of the conquest and evangelisation, buildings were beginning to be constructed in Europe according to Renaissance criteria; in Spain, the process of change towards the new architectural trend was slower, as late Gothic criteria persisted. Some of these are: the design of the structure around the cloister and with a very compact typology.

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The complex presents architectural uniformity, with a spatial pattern according to the conditions or characteristics of the site where they were erected, with constructive homogeneity, as the building process was controlled by the Spanish, 'moderate' or standardised layout, without sumptuousness in the convents [with the exception of the Augustinians], using moderate resources, freedom in design, and the layout had to be approved by the viceregal master builder [Reyes, 2016].

It should be remembered that Franciscans, Dominicans and Augustinians built enormous open buildings for worship and catechesis. They generally consist of a single-nave church with a convent and cloister, plus atrium[s], four chapels, an open chapel with an altar and a monumental cross located in the geometric centre of the atrium or in line with the chapel altar [Lara, 1996, p.8].

Façade. The components of the façade are as follows: in the centre is the door with a semicircular arch, which is framed by an alfiz or arch of Mudejar architecture, crowned by a pediment. At the top of the pediment is the choir with a mullioned window or window divided into two parts. The tower is located to the right of the gate with an embrasure, which is topped with a bell tower. On the left side, there is a 45-degree buttress. To the right in the background is the open chapel, which has a lowered arch on the upper floor and is framed by a simple alfiz or moulding. [Ortiz, 2013]. [Figure 1].

Box 1

Figure 1

Entrance to the church of the former Franciscan convent of the Assumption of Our Lady, founded by Friar Diego de Olarte and built in 1650.

Source: own

Atrio. The word **'atrium'** means 'portico or entrance to a large house.' The atrium is a space for gathering, instruction, and spatial distribution, located between the temple and the street [Cathechesis of the Good Shepherd, 2014].

The atrium is also defined as a dynamic architectural space whose function was to be the social, religious, and cultural centre of the convent. The atrium was an educational and professional training centre for the community.

This space is delimited by one or two masonry walls and was associated with the adjacent town square, thus increasing its power as an urban landmark. Pre-Hispanic rites favoured the relationship between man and nature, so it can be assumed that people felt more comfortable in outdoor spaces. This was taken into account by the friars who, in their evangelising activities, had to understand the mentality of the natives and consider open spaces [Reyes, 2016].

The atrium is an outdoor space, used during the 16th century, whose predominant shape was quadrangular. It was used as a strategy to bring together large groups of people, reviving the concept of open space or ceremonial square, which became impressive spaces alongside the compact volumes represented in the temples and convent areas of monasteries, fitting together in the same architectural structure.

The atrium is considered to contain the open chapel, the posas chapels, and the processional path. In the case of the Tochimilco complex, there are three symmetrical entrances that give access to the central corridor [López and Frausto, 2019] ... 'The complex has a large rectangular atrium with two entrances and crenellated walls' [Ortiz, 2013, p. 35].

In the constructions of the first religious centres, the atrial courtyard was a connecting element between the open chapel and the posas chapels. These sites were important in the early days of evangelisation, until the temples were completed.

This contrasts with the idea that the atriums and posas chapels were used because of the indigenous population's fear of enclosed spaces. This is because pre-Hispanic religious rituals were celebrated outdoors and they were unfamiliar with the architectural forms of the semicircular arch and the vault; however, these construction elements must have been added long after the early stages of evangelisation [García, 2015].

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The atrium cross. At the beginning of the Spanish conquest of Mexico [1521], the crosses were made of wood, but from 1539 onwards, under Church ordinance, they were replaced by stone crosses. The cross contains iconographic elements at the top relating to the passion and crucifixion of Christ [López and Frausto, 2019] ... 'The most common form is a cross without a corpus; rather, the instruments of the Passion are carved into the shaft and arms' [Lara, 1996, p.8]. The atrium cross within the religious complex in Tochimilco is located in the centre of the atrium on the longitudinal axis from the entrance to the atrium to the entrance to the temple. The stone cross stands on pedestals or bases [López and Frausto, 2019] and had an educational function with pre-Hispanic reliefs and Christian symbols [Reyes, 2016]. [Figure 2]

Box 2

Figure 2

Central aisle, atrial cross, the temple in the centre and the Indian chapel on the right.

Source: own

Procession route. This is the name given to the path or route that parishioners take within the temple courtyard, praying, singing and even remaining silent as an act or celebration of their religious faith [López and Frausto, 2019]..."In 16th-century courtyards, it is usually perimeter-based and separated from the centre of the courtyard by a row of trees or a wall; the procession would stop at each of its four corners, in buildings that were made specifically for this purpose and were called 'posas' chapels [Mengual, n.d.].

Pilgrims' gate: Located to the west of the former convent, it is in keeping with the proportions of the rest of the convent. It is believed that the portal served as an open chapel, as there are elements indicating that there are two early mud-brick arches [provisional sacristy] on the site [López and Frausto, 2019]. In the case of the Temple and former convent of La Asunción, there is a perimeter walkway with niches [Figure 3].

Box 3

Figure 3

Processional route and niches attached to the wall.

Source: own

Chapel. 'The origin of the word chapel comes from the Latin cappella, diminutive of cappa, meaning cloak, so the architectural construction could correspond to the formal representation of a cloak that shelters and protects' [García, 2015, p. 17].

Chapel posa. Chapels posas were placed in the corners of the atrium, which was a square or rectangular building protected by a vault. These chapels were used as part of the rites in processions, where the Blessed Sacrament was 'rested'. The posa chapel was a religious, social and political space, which was erected at the corners of the atrium with vaulted or false vaulted roofs. They were used as stations or stops for processions, with each posa chapel belonging to a different social group of indigenous people [Reyes, 2016].

Open chapel. Outdoor worship originated in the early days of the Christian religion, although in the pagan tradition it was also practised in open spaces. There were ceremonies at certain times of the year that were held outside the temple, but in the Christian religion it has a reduced value within the celebrations [Gussinyer, 1996].

The 'courtyard chapel' or 'Indian chapel' in the New Spain era was considered a space where the conquered were evangelised. The courtyard was later identified as an 'atrium'. Confusion may arise between the 'courtyard chapel' and the courtyard, which is also called an 'atrium,' as the latter was often part of the courtyard chapel [García, 2015]. Open chapels were considered isolated buildings, as they are independent of the temple and occasionally had an annex that served as a dwelling for the friars. Almost all 16th-century monasteries in Mexico have an open chapel, except for Anenecuilco in Cuautla, Morelos, and Temimilcingo in Tlaltizapán de Zapata, Morelos [Reyes, 2016].

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The first temporary constructions, built by religious orders, had a transcultural meaning in simple thatched buildings [reeds and a simple shed] of the indigenous population and the reuse of the foundations or platforms of existing civil buildings. Although simple arbours were initially built, more complex constructions known as arboured chapels were later erected, where Christian worship was consolidated.

These temporary constructions already had a roof or nave and the layout of a Christian temple built with wattle and daub walls and a cane roof. However, the hot climate and the insufficient space in these constructions to accommodate the parishioners opened up the interior space to the courtyard, giving way to the open chapel. In these constructions, the atrium is delimited by a roof for protection from the environment, and the integration of the analogies of the pre-Hispanic temple and the Christian temple can be observed: presbytery-teocalli, courtyard-plaza. By 1530, these temporary constructions were replaced by permanent ones, either attached to the convent temple or as balconies [Reyes, 2016].

Within the field of colonial religious architecture, the importance of the chapel lies in the fact that it was the basis for the construction of convent complexes, churches, or abbeys. It can be said that the first chapels in Mexico were temporary structures which, once they had served their purpose, were replaced by chapels made of durable materials. For this reason, chapels were sometimes integrated into the nave of temples as side chapels, into the apse or as independent structures [García, 2015].

Chapel of the Third Order. The Chapel of the Third Order, so called because it corresponds to the Franciscan tertiary community. Located to the west of the former convent and to the east of this chapel is a cistern [water tank] [López and Frausto, 2019].

The temple. The Catholic temple is a building where God is worshipped and has different components such as the presbytery, seat, altar, ambo, tabernacle, parish, confessional, holy oils, choir, baptismal font, collection boxes, credence table and sacred images. The temple is a spatial unit for the community that is designed in relation to liturgical functions and becomes a supernatural symbol.

In addition, the temple is a meeting place that should convey trust and closeness between the faithful and the clergy in large spaces [Mollor, 2019].

The temple has a flat nave with a rectangular presbytery, covered with ribbed vaults. The convent has two levels and a two-level cloister covered by coffered ceilings in the Mudejar style, supported by columns with lowered arches. The upper part of the columns has mural paintings and a Franciscan cord surrounds the entire cloister [Ortiz, 2013].

The roofs are called ‘par y nudillo’ [pair and knuckle], which consists of sloping beams supported by the ridge or upper vertex.

The beams are arranged in pairs or rafters [Asociación Almerón, n.d.]. Mudejar architecture [Hispanic-Muslim architecture] in Mexico was adapted to other needs, climatic and topographical conditions; therefore, it is not possible for a building to be properly Mudejar. There is historical evidence that Mudejar wooden structures [Ortiz, 2013]

One of these important structural contributions is the wooden roofing system.

There is evidence in historical sources that there was already precise knowledge of how to build this type of roof in New Spain, but unfortunately few have survived. ‘Some are found in the state of Puebla, where there is also one of the truss and knuckle structures which, together with the one in Tlaxcala in Nuestra Señora de la Asunción, are the best examples we have in our territory’ [Ortiz, 2013, p.21].

Presbytery. The presbytery is a space that is integrated into the temple, and its importance is emphasised by means of platforms. The priest's seat is the seat of the priest and should not be confused with a throne. The design of presbyteries is almost uniform: polygonal with variations. The most common shape is trapezoidal, in which the depth of the polygonal presbytery measures more than half the width of the nave from the arch that connects it to the nave. In the case of Tochimilco, the presbytery is like a box that has been added on [Mollor, 2019].

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Seat. The seat is the space that allows communication between the priest and his parishioners. It is the seat reserved for the priest, who presides over the celebration in the name of Christ, where religious ceremonies are presided over and the prayers of the people of God are guided [Parroquia NSR, n.d.].

Altar. The altar is the table of Christ, where the sacrifice of the cross is represented according to the sacramental signs and the Eucharist. The altar should occupy the centre of the space, so that the attention of the faithful is on the celebration of Mass, and the temple should not have two or more altars [Mollor, 2019].

The apse. The apse is the element that covers the altar and represents ¾ of the width of the module. The buttresses represent ¼ of the module and the walls represent 1/8 [López and Frausto, 2019].

Ambo. The ambo or pulpit is the fixed, well-lit space where the word of God is proclaimed [Mollor, 2019].

Choir. The choir can be located in various places, but it is integrated into the community [Mollor, 2019]. [Figure 4]

Box 4

Figure 4

Choir covers

Source: own

Chapel of Reconciliation. The reconciliation chapel may be located near the entrance or in relation to the baptistery [Mollor, 2019].

Baptismal font. The baptistery is the area where the baptismal font or fountain is located, which must be illuminated as the person is reborn of water and the Holy Spirit as a Christian. This place can be located inside the temple or in a chapel [Mollor, 2019].

Sacristy. It has 1/2 module to the west of the apse [López and Frausto, 2019].

Nave. The width of the nave is established as the governing module, which is repeated 12 times in the west-east direction and 15 times in the north-south direction. The length is 4.5 modules [López and Frausto, 2019]. After the 2017 earthquakes, studies were carried out in different areas of the former convent in Tochimilco to identify its structural conditions, and a mass of water was found in the subsoil of the nave

Flat nave. A nave rasa is known as a nave with two horizontal friezes, or continuous space, with a central axis from the entrance to the presbytery [preceding the high altar]; sotocoro [under the choir, usually with an arch], choir [space for choristers or singers], the nave for the congregation, baptismal fonts, access to the cloister and, in the opposite direction, a door to the atrium, another door to the presbytery and the ante-sacristy [access space to the sacristy] and from there to the sacristy [where ornaments are kept and priests are dressed] [Artigas, 1999].

The flat nave refers to a smooth nave without interruptions, which has no side chapels. The single-nave temple is the dominant architectural form of the temples along the 16th-century route. Kubler relied on the research of the Augustinian friar Gerónimo Román, and therefore maintains that the temple is a Mexican model with primitive simplicity; although there are variations, such as the temples of the Dominican order, where there is a transept and side chapels [Kubler, 1992].

The temples along the route are characterised by a vaulted nave with a large interior capacity, which at the time of construction was not part of the medieval Spanish architectural programme, but did exist in Occitania and the Catalan-Aragonese Confederation. The solution for the churches was to use the basilica type with three naves and a wooden roof, which was replaced by a vaulted nave, the length of which would be greater than that of churches from the same period and later periods in what is now Mexico [Gussinyer, 1996]. [Figure 5].

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Box 5

Figure 5
Interior of the temple showing the altar

Claustral. The cloister is generally two storeys high, with three aisles and rarely three aisles around a central courtyard with a portico [columns and arches supporting a roof], communal services such as a porter's lodge, kitchen, refectory [dining room], field portal, profundis room [prayer area before meals], access to the ante-sacristy and sacristy; the friars' rooms [cells] were located on the upper floor, and finally, the latrines and bathrooms were located towards the garden [Artigas, 1999]. The cloister in Tochimilco is located on one side of the temple, facing east-west. It is a prism that protrudes but does not reach the height of the temple. It is 1/2 module wide and its walls are 1/8 thick [repeated in the floor plan]. Two construction stages of the convent have been identified: 1540-1550 and 1560-1570. The first stage is believed to have been built with materials from the region, although some chroniclers mention that the construction of religious buildings was due to the use of sites where pre-Hispanic religious sites already existed. In this way, the evangelisers observed the religious tradition and replaced it with the Catholic faith. In addition, they took advantage of the foundations and even the construction materials of buildings that predated this period. The second stage is when the lime and stone construction was carried out, by order of Viceroy Antonio de Mendoza [López y Frausto, 2019].

Refectory [dining room]. Located to the south of the cloister, there is an element that for a long time was believed to function as a refrigerator; however, studies in 2018 determined that its function was structural [López and Frausto, 2019].

Additions [annexes]. Located to the east of the convent, modifications were made in the 19th and 20th centuries to meet specific needs, which is why they are not related to the complex in terms of their architectural planning with geometric foundations [López and Frausto, 2019].

Garden. There are ruins of walls that delimit the space.

In terms of construction elements, 16th-century monasteries are characterised by foundations with a depth of up to 1.70 m [2 Castilian varas], in rectangular or quadrangular prisms to support the foundation. The foundations were wider than the walls [load], as they protruded 20 centimetres on each side.

It should be noted that, in the case of soft or unstable ground, the dimensions were variable. However, the walls [1.60 m to 2.40 m thick] are not very efficient at withstanding forces perpendicular to their plane [thrust from vaults or earthquakes]. Buttresses, abutments or reinforcements are located on the outside of the walls, supporting the thrust produced by the vaulted roof. Vaults or domes correspond to a symbolic scheme and a structural scheme that allows large spans to be covered. It is common to use groin vaults or barrel vaults, which transmit the thrust to the foundation by means of pilasters [Martínez, 2020].

In the buildings belonging to the Route of the Convents, construction elements such as medieval barrel vaults and Roman technology were mixed. However, the earthquakes of September 2017 damaged all the convents, nine of which suffered serious damage. The lack of resources for their restoration has left them in a state of total abandonment or 'in progress.' The INAH, National Institute of Anthropology and History, shored up the damaged elements of the buildings, but the rescue work was abandoned [García and Gómez, 2023].

The nine buildings that the various experts reported as having significant structural damage were classified as 'severe damage' [Figure 6]: Former Convent of Nuestra Señora de la Asunción, Cuernavaca Cathedral, Morelos; Temple and former Convent of San Miguel Arcángel, Huejotzingo, Puebla; Temple and former Convent of Santiago Apóstol, Ocuituco, Morelos; Temple and former Convent of San Juan Bautista, Tetela del Volcán, Morelos; Temple and former Convent of San Guillermo, Totolapan, Morelos; Temple and former Convent of San Juan Bautista, Yecapixtla, Morelos; Temple and former Convent of San Juan Bautista.

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Tlayacapan, Morelos; Temple and former Convent of the Immaculate Conception. Zacualpan de Amilpas, Morelos and Temple and former Convent of the Assumption of Our Lady, Tochimilco, Puebla. Of these 15 temples and former convents in New Spain, nine were severely damaged.

These are the ones that require the most intervention and investment. In the temple and former convent of the Assumption of Our Lady, Tochimilco, Puebla, there are longitudinal fractures and cracks in the vaults, as well as detached ribs.

Other damaged architectural elements include the vault and façade of the open chapel and the cloister. Architect Francisco Pérez de Salazar was responsible for conducting the first analysis of the former convent and temple in Tochimilco. In that initial assessment, the architect observed that a huge crack ran across the bell tower and that 75 per cent of the temple's vaults, walls and arches were fractured. The temple's current problems are the result of previous work.

However, the damage to the complex is not due to the way the building was designed and constructed. The origin of the damage is the way in which the restoration work on the building was carried out in 1999 [García and Gómez, 2023].

In 2018, the Mexico office of the United Nations Educational, Scientific and Cultural Organisation [UNESCO] allocated resources for the reconstruction of the walls surrounding the atrium because it was considered a “living place” that maintains the social cohesion of the Tochimilco community. After the 2017 earthquake, some pinnacles were affected in the middle by cracking in the middle of the element due to high shear forces and damage from bending or flexural compression.

Box 6

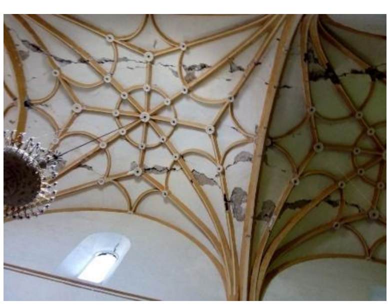

Figure 6
Damage to the roof caused by the 2017 earthquake.
Source: own

Conclusions

The commercial importance of trade routes in the development of cities and communities has led to the construction of important buildings, as these trade routes not only transport goods, but also generate heritage and culture. One such route is the circuit between the states of Morelos and Puebla, which gave rise to the 16th-century Monastery Route.

The 16th-century convent complexes became symbolic landmarks of power, which is why the different centres share common characteristics. One common feature is that the buildings are fortress-like, with uniform architecture and construction. The atrium stands out in these buildings. Some say it has Mesoamerican origins, others say it is European, and still others say it is a coincidence. Regardless of its origin, it is the community centre in many towns in Mexico.

The atrial cross became the centre of the atrium, surrounded by the processional path and the pilgrims' portals as the ‘vestibule’ of the complex. Unfortunately, the 2017 earthquake affected the temple, keeping it closed until now, but the atrium is still in use as a community centre. Although the earthquake severely affected the building, the damage was accentuated by the 1999 intervention.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Contribution of the authors

Morales-Ortega, Alejandro: Contributed to the conception of the project idea, document review, methodology, analysis of results and conclusions.

Vázquez-Torres, María del Rayo: Contributed to the conception of the project idea, document review, theoretical framework, conclusions and as corresponding author.

Navarrete-García, Mónica: Contributed to the introduction, methodology, preparation of the graphic summary, and analysis of results.

Availability of data and materials

The articles analysed in this research can be found in the UNAM Journal Catalogue, INHA Journal, Dialnet, Clacso, Radalyc, and Google Scholar databases.

Abbreviations

COVID-19	Pandemic caused by the SARS-CoV-2 coronavirus
FONDEN	Mexico Natural Disaster Fund
INAH	National Institute of Anthropology and History
UNESCO	United Nations Educational, Scientific and Cultural Organisation

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Article

Static and dynamic seismic analysis for the construction of structural concrete portal frames in Manzanillo, Colima

Análisis sísmico estático y dinámico, para la construcción de marcos pórticos de concreto estructural en Manzanillo, Colima

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Abstract

The port of Manzanillo is located on the Mexican Pacific coast, due to its proximity to the Cocos Plate and the North American Plate, it has had significant events recorded from 1932 [where three earthquakes occurred on the coast of Colima and Jalisco with a magnitude greater than 7] until January 12, 2025 with an epicenter in Coalcoman, Michoacan with a magnitude of 6.1. The goal is to determine the basal shear, direct shear and torsional shear, as well as the angular frequencies and nodal stiffnesses of a building consisting of four concrete portal frames. The results were the determination of tangential forces, as well as moment in columns and beams in each floor. It is concluded that the application if the E.030 Seismic Resistant Designs Standard gives us the certainty that the relative displacements are within the standard, and the calculated eccentricities are adequate for an asymmetric architectural plan.

Shear, Frequency, Stiffnesses

Resumen

El Puerto de Manzanillo se encuentra ubicado en las costas del pacífico mexicano, por su proximidad a la Placa de Cocos y la Placa de Norteamérica, ha tenido grandes eventos significativos registrados a partir de 1932 [donde ocurrieron tres sismos en las costas de Colima y Jalisco superior a 7 de magnitud] hasta el 12 enero de 2025 con epicentro en Coalcomán, Michoacán con magnitud de 6.1. El objetivo es determinar el cortante basal, cortante directo y cortante torsional, así como las frecuencias angulares y las rigideces nodales de una edificación que consta de 4 marcos pórticos en concreto resultado. Los resultados fueron la determinación de fuerzas tangenciales, así como momento en columnas y trabes en cada entrepiso. Se concluye la aplicación de la Norma E.030 Diseño Sismorresistente, nos da la seguridad que los desplazamientos relativos están dentro de la norma, y las excentricidades calculadas son adecuadas para una planta arquitectónica asimétrica.

Cortante, Frecuencia, Rigidez

Area: Advocacy and attention to national problems

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Introduction

The port of Manzanillo is the country´s main exported to the Pacific. Through it operate routes to Japan; Hong Kong, Australia and New Zealand [Guzman, 1995]. Due to its geographical location, it is the best link with the industrial and commercial areas of the country, which has established itself as one of the most important ports in Mexico for its commercial activity and exchange of products of all kinds for the West, as shown in figure 1 [SEMAR, 2018].

In seismic engineering the only way to prevent the occurrence of disasters caused by natural hazards is by means of characterization and studies that allow taking preventive measures to be taken and, when appropriate, mitigation measures for possible disaster scenarios [Núñez, 2012].

The state of Colima is one of the regions with the highest seismicity in the country and therefore where the seismic hazard is very high, however this hazard is not only due the subduction process of the tectonic plates, but also to other unidentified continental structures that have generated new historical earthquakes.

The goal of this work is to review and evaluate the historical seismicity of the state of Colima as well as correlate recent seismicity data, related and carried out in the region.

Box 1

Figure 1
Satellite image of the port of Manzanillo
Source: earthgoogle.com

Background

Seismological context and seismic regionalization for the state of Colima

At the national level, the seismic hazard of the country is divided into four main zones ranging from A to D, where A represent low seismicity and D representing a very high seismic hazard.

In the seismological context, the state of Colima, including Manzanillo, is located in zone D. The threat is generated mainly in the so-called Jalisco block located by the convergence of the Cocos Plate, the Rivera Plate and the North American Plate in the Pacific coastal zone [Garduño, *et al*, 1998]. México is located between the aforementioned plates in the so-called belt of fire, characterized by the presence of very active volcanoes and high seismicity.

The most destructive earthquakes in the country have occurred on the border between the aforementioned plates [with magnitudes greater than 7 on the Richter scale and intensities of VIII on the Modified Mercalli scale], causing severe damage in cities such as Colima, which is located in zone D, Guadalajara [seismic zone C] and in the states of Michoacán and México, as seen in table 1 and figure 2.

Box 2

Table 1
Main earthquakes that occurred in the Colima-Jalisco region.

No.	Date	Latitude N	Length W	Magnitude Mw	Intensity MMI	
1	03-06-1932	19° 80´	104° 00´	8.0	VIII	R and NA
2	18-06-1932	18° 95´	104° 42´	7.8	IX	Replica of 1
3	15-04-1941	18° 85´	102° 94´	7.6	X	C and NA
4	30-01-1973	18° 39´	103° 21´	7.6	VIII	C and NA
5	09-01-1995	18° 79´	104° 47´	8.0	VII	R and NA
6	21-01-2003	18° 63´	104° 13´	7.5	VIII	C and NA

Source: UCOL et al., 1997, Zobin. 2004 and Preciado, 2011

Box 3

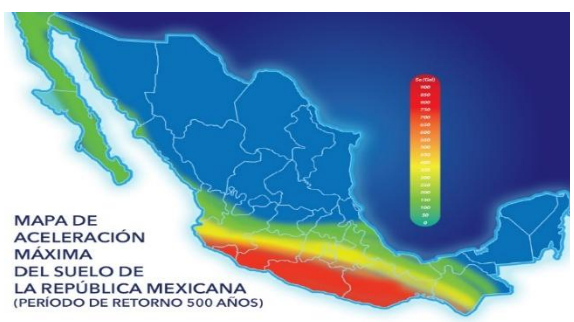

Figure 2
Map of maximum ground acceleration of the Mexican republic [Return Period 500 years].
Source:https://www.uv.mx/cienciauv/blog/hablemosunpocosobreamenazasismic/

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State or art

Soil liquefaction: causes, effects and solutions
Soil liquefaction can occur when saturated loose sands experience a loss of strength and stiffness under the repeated application of a large load, such as during an earthquake. The cyclic stress causes a rapid increase in pore water pressure, which decreases the strength soil strength. Under these conditions, the sands begin to flow like a liquid [Lees, 2024].

On the other hand, the earthquakes in Mexico and Chile have left experiences and lessons learned about the importance of redesigning new structures based on stricter regulations, in order to reduce the risk of disaster, as well as implementing safety protocols for earthquakes and tsunamis.

For example, in Mexico, the 1985 and 2017 earthquakes remind us of the vulnerability of living in a highly seismic zones, we must continue to train ourselves in civil protection and allow us to act appropriate to prevent risk situation [Salcido, 2020].

The structural conception

The general process of activities that lead to a structural project, implies a series of work stages, which require a sequence and the same time an interdependence of the same, these stages can be considered as basic activities structural design [González, 1990].

a) Structural design
b) Load analysis
c) Structural analysis
d) Dimensioning

The structure conception will be the result of experience imagination and above all of the intuitive ability of the designer, but this professional intuition can only be developed with a good academic support and constant and updated professional practice [Corrales, 2010].

As an experience in Manzanillo in the 1995 earthquake, as a society-government we did very badly because we did not give the importance that is due to the structural design, most of the collapsed buildings had deficiencies, some of the most characteristic were:

a) Irregular "T" or "L" shaped floors that caused strong torsions.
b) Concentration of masses in upper levels
c) Corner buildings exposed to unacceptable torsional stresses
d) Vulnerability of buildings with very flexible soils.

Methodology [Static Method Analysis]

Vertical distribution of the basal shear

Known as basal shear V in the two orthogonal directions, it is distributed over the total height of the building, where the masses are supposed to be concentrated in the floors, since the design acceleration should be an increasing function of the height above ground when causing horizontal accelerations, the structure will deform laterally, and its accelerations will be greater than those of the ground on which it rests.

Shear force at the base

The shear force at the base of the structure, corresponding to the direction considered, will be determined with the following expression:

$$V = \frac{Z\,U\,C\,S}{Ro}\,P \qquad [1]$$

Zoning

The Mexican territory is considered to be divided into four zones as shown figure 2. The proposed zoning is based on the spatial distribution of observed seismicity, the general characteristics of earthquake movements and their attenuation with epicentre distance.

Each zone is assigned a z-factor, as shown in table 2, this factor is interpreted as the maximum horizontal acceleration in rigid soil with a 10% probability of being exceeded in 50 years, the z-factor is expressed as a fraction of the acceleration of gravity.

Use Factor [U]

Each structure must be classified according to the type of building. The use factor or importance [U] will be used according to the classification made. For buildings with seismic isolation at the base, U = 1 may be considered [Ministerio de Vivienda, Construcción y Saneamiento, 2003].

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Fundamental period of vibration [T]

The fundamental period of vibration for each direction shall be estimated with the following expression:

$$T = \frac{hn}{Cr} = \frac{14}{35} = 0.40$$
[2]

when:
hn = total building height = 14 m
Cr = 35 for buildings whose resistant elements in the considered direction are only:

a) Reinforced concrete frames without shear walls.
b) Ductile seal frames with moment resisting connections, without bracing

Box 4

Table 2

Zone factor

Zone	Z
4	0.45
3	0.35
2	0.25
1	0.10

Source: *Technical standard E.030 "Earthquake resistance design"*

Box 5

Table 3

Soil factor [S]

	S0	S1	S2	S3
Z4	0.80	1.00	1.05	1.10
Z3	0.80	1.00	1.15	1.20
Z2	0.80	1.00	1.20	1.40
Z1	0.80	1.00	1.60	2.00

Source: *Technical standard E.030 "Earthquake resistance design"*

Box 6

Table 4

Period defining the value of the C-factor [Tp] and period defining the beginning of the C-factor zone with constant displacement [T_L]

	Soil profile			
	S0	S1	S2	S3
Tp [seg]	0.30	0.40	0.60	1.00
T_L [seg]	3.00	2.50	2.00	1.60

Source: *Technical standard E.030 "Earthquake resistance design"*

Seismic amplification factor [C]

According to the site characteristics, the seismic amplification factor [C] is defined by the following expressions:

$$T < Tp \qquad C = 2.5$$
$$Tp < T < TL \qquad C = 2.5\left(\frac{Tp}{T}\right)$$
$$T > TL \qquad C = 2.5\left(\frac{Tp * TL}{T}\right)$$

For our case C = 2.5, due to the fact that our soil is S3, therefore the value of Tp = 1.00.

Coefficient of reduction of seismic forces [Ro]

Structural systems are classified according to the materials used and the seismic-resistant structuring system in each direction of analysis, as shown in table 4.

Box 7

Table 5

reduction coefficient in structural elements

Structural system	Basic reduction coefficient [Ro]
Steal Moment resisting frames Concentrically braced frames Eccentrically braced frames	 8 8 8
Reinforced concrete Portal frames Dual Structure walls	8 7 6 4
Reinforced confined masonry	3
Wood [For permissible stresses]	7

Source: *Technical standard E.030 "Earthquake resistance design"*

Lateral stiffness

The form of vibration of the building is a function of the masses $\left(\frac{w}{g}\right)$ and the stiffness of the supporting elements, the latter is called floor stiffnes7s or spring constant and is defined as the ratio of the shear force $[V]$ on the floor under study to the relative displacement $[\Delta]$ of the two levels that limit it.

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The stiffness will depend on the greater or lesser stiffness of the column or wall itself and the rotation of the ends [nodes] according to the stiffness of the beams and columns concurrent to the node.

Angular frequencies [wi] and natural modes of vibration

A vibrating structure has four basic properties: mass, stiffness, damping and displacement, a mechanical vibration is the oscillation of the mass around its equilibrium point the nature of the oscillation is determined not only by the mass but also by the stiffness and damping in nature [Molero, 2016].

Chopra [2014] proposed the determinant matrix for trivial solution which is mentioned below:

$$wi = Det\ (k) - (w1^2\ M) = 0 \quad [3]$$

Expanding the determinant yields a polynomial of order N at $w1^2$, equation 3 is known as characteristic equation or frecuency equation. This equation has N positive roots the structural mass and stiffness matrices are symmetric and positive definite.

The positive definite matrix property of K is ensured for all structures supported in such a way as to prevent the motion of rigid body, as is the case with civil engineering structures *[ibid]*.

Results

The results obtained were the load metering for a four-level structural concrete portal frames, as well as the seismic weight, the calculation of the basal shear, direct shear and torsional shear for the port of Manzanillo, which as previously mentioned is a zone of very high seismicity, these results were obtained from the Seismic Resistant Guadalajara regulation and the Technical Standard E.030 “Earthquake Resistant Design” of Peru. [Rupay, 2023].

Load metering:

– Weight of the beams = 44.77 ton*f
– Slab Weight = 36 ton*f
– Weight of finishes and partition walls = 30 ton*f
– Weight of columns = 41.47 ton*f
– Weight of overload = 30 ton*f
– Weight of roof overload = 12 ton*f

Box 8

Table 5

Load metering and seismic weight

Level	beam	column	slab	finishes	LL	DL	Ps
1	43.7	29	36	30	30	138.7	153.7
2	43.7	37.3	36	30	30	147	162
3	43.7	37.3	36	30	30	147	162
4	43.7	17.6	36	30	12	127.3	133.3

Source: *Caro, 2025*

Obtaining Basal shear

$$V = \frac{0.45 * 1.0 * 2.5 * 1.10}{8} * 611 = 94.5\ ton$$

when:
Z = 0.45 [Zone four]
U = 1.00 common use [dwellings and offices]
C = 2.5 because $T < Tp$
S = 1.10 because it is a very poor soil and belongs to Z4
Ps = 611 ton, total seismic weight of the building
Distribution of seismic force at each level
The horizontal seismic forces at any level i, corresponding to the direction considered are calculated with the following equations:

$$Fi = \alpha * V \quad [4]$$

$$\alpha = \frac{Pi\ (hi)^k}{\sum_{j=1}^{n} Pj\ (hj)^k} \quad [5]$$

Box 9

Table 6

Title: Distribution of seismic forces

Level	h	H	Ps	PH^k	αi	Fi
1	4.0	4.0	153.7	614.8	0.1096	10.35
2	3.6	7.6	162	1231.2	0.2195	20.74
3	3.6	11.2	162	1814.4	0.3235	30.57
4	3.4	14.6	133.3	1946.6	0.3471	32.8
				Σ = 5607	Σ = 1.0	Σ = V

Source: *Caro, 2025*

Lateral stiffness

$$Kc = \frac{12\ EI}{h^3} \quad [6]$$

when:
$f'c = 250\ kg/cm^2$

$$I = \frac{0.60^4}{12} = 0.0108\ m^4$$

replacing:

$$K1c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{4^3} = 4834.74\ tonf/m$$

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Kc = 58016.72 tonf/m, for level 1

$$K2c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{3.6^3} = 6632\ tonf/m$$

Kc = 79,584 tonf/m, for level 2 = level 3

$$K4c = \frac{12 * 151000 * \sqrt{250} * 0.0108}{3.4^3} = 7872.54\ tonf/m$$

Kc = 94470.55 tonf/m, for level 4

Having a calculated the stiffness of all the columns of the building, we apply the displacement matrix:

$$F = [K * U] \rightarrow U = [K^{-1} * F] \quad [7]$$

The calculation of the matrix of lateral stiffness and seismic forces is show below:

$$k = \begin{bmatrix} (k1+k2) & -k2 & 0 & 0 \\ -k2 & (k2+k3) & -k3 & 0 \\ 0 & -k3 & (k3+k4) & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$k = \begin{bmatrix} 137600 & -79584 & 0 & 0 \\ -79584 & 159168 & -79584 & 0 \\ 0 & -79584 & 159168 & -94470 \\ 0 & 0 & -94470 & 94470 \end{bmatrix}^{-1}$$

$$F = \begin{bmatrix} 10.35 \\ 20.74 \\ 30.57 \\ 32.8 \end{bmatrix}$$

$$U = k^{-1} * F$$

$$U = \begin{bmatrix} 0.004 \\ 0.0068 \\ 0.0094 \\ 0.0097 \end{bmatrix} \text{m}$$

Finally, it is verified that the displacements comply with the Peru seismic-resistant technical standard, the drift is calculated, that is to say, the relative displacement of each level between the corresponding height.

$$\Delta i = \frac{u_{i+1} + u_i}{hi} * 0.75\ R \quad [8]$$

$$\Delta = \begin{bmatrix} 0.006 \\ 0.0046 \\ 0.0043 \\ 0.00005 \end{bmatrix}$$

Which complies with the maximum relative displacement, calculated with equation 8, should not exceed the fraction of the height of the mezzanine, that for reinforced concrete is:

$$\left(\frac{\Delta 1}{hei} = 0.007\right)$$

The stiffness of columns and beams were obtained using Wilbur formulas, conditioned for regular frames with elements of constant inertia and when the beams are stiffer that the columns, since this method gives errors of less than 10% in the floor to ceiling distortions as follows:

$$R1 = \frac{48\ E}{h1\left[\frac{4\ h1}{\sum kc1} + \frac{h1+h2}{\sum kv1 + \frac{\sum kc1}{12}}\right]} \quad [9]$$

$$R1 = \frac{48 * 2{,}188{,}198}{4\left[\frac{4*4}{0.0081} + \frac{4.00+3.60}{0.00288 + \frac{0.0081}{12}}\right]}$$

R1 = 6384 ton/m

$$R2 = \frac{48\ E}{h2\left[\frac{4\ h2}{\sum kc2} + \frac{h1+h2}{\sum kv1 + \frac{\sum kc1}{12}} + \frac{h2+h3}{\sum kv2}\right]} \quad [10]$$

$$R2 = \frac{48 * 2{,}188{,}198}{3.60\left[\frac{4*3.60}{0.009} + \frac{4+3.60}{0.00288 + \frac{0.0081}{12}} + \frac{3.60+3.60}{0.00288}\right]}$$

R2 = 4677 ton/m

$$R3 = \frac{48\ E}{hn\left[\frac{4\ h3}{\sum kc3} + \frac{h2+h3}{\sum kv3} + \frac{h3+h4}{\sum kv4}\right]} \quad [11]$$

$$R3 = \frac{48 * 2{,}188{,}198}{3.60\left[\frac{4*3.60}{0.009} + \frac{3.60+3.60}{0.00288} + \frac{3.60+3.40}{0.00288}\right]}$$

R3 = 4467.6.62 ton/m

$$R4 = \frac{48\ E}{h4\left[\frac{4\ h4}{\sum kc4} + \frac{h3+h4}{\sum kv3} + \frac{h4+h0}{\sum kv4}\right]} \quad [12]$$

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$$R4 = \frac{48 * 2{,}188{,}198}{3.40\left[\frac{4 * 3.40}{0.00953} + \frac{3.60 + 3.40}{0.00288} + \frac{3.40}{0.00288}\right]}$$

R4 = 6132 ton/m

Total x-axis stiffness in the four frames
K_1 = 25,536 ton/m, level 1
K_2 = 18,709 ton/m, level 2
K_3 = 17,870 ton/m, level 3
K_4 = 24,528 ton/m, level 4

$$k = \begin{bmatrix} (k1+k2) & -k2 & 0 & 0 \\ -k2 & (k2+k3) & -k3 & 0 \\ 0 & -k3 & (k3+k4) & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$k = \begin{bmatrix} 44245 & -18709 & 0 & 0 \\ -18709 & 36579 & -17872 & 0 \\ 0 & -17872 & 42398 & -24528 \\ 0 & 0 & -24528 & 24528 \end{bmatrix}$$

$$\lambda i\ m = \begin{bmatrix} 15.66\ \lambda i & 0 & 0 & 0 \\ 0 & 16.51\ \lambda i & 0 & 0 \\ 0 & 0 & 16.51\ \lambda i & 0 \\ 0 & 0 & 0 & 12.07\ \lambda i \end{bmatrix}$$

$$\lambda i = \begin{bmatrix} 192.46 \\ 1665.54 \\ 3740.27 \\ 5362.15 \end{bmatrix}$$

$$wi^2 = \begin{bmatrix} 13.87 \\ 40.811 \\ 61.15 \\ 73.22 \end{bmatrix}$$

Therefore, the frequency periods at each level are equivalent to:

Level 1

$$T1 = \frac{2\pi}{w1^2} = \frac{2 * 3.1416}{13.87} = 0.453\ seg$$

Level 2

$$T2 = \frac{2\pi}{w2^2} = \frac{2 * 3.1416}{40.611} = 0.153\ seg$$

Level 3

$$T3 = \frac{2\pi}{w3^2} = \frac{2 * 3.1416}{61.15} = 0.102\ seg$$

Level 4

$$T3 = \frac{2\pi}{w4^2} = \frac{2 * 3.1416}{73.22} = 0.085\ seg$$

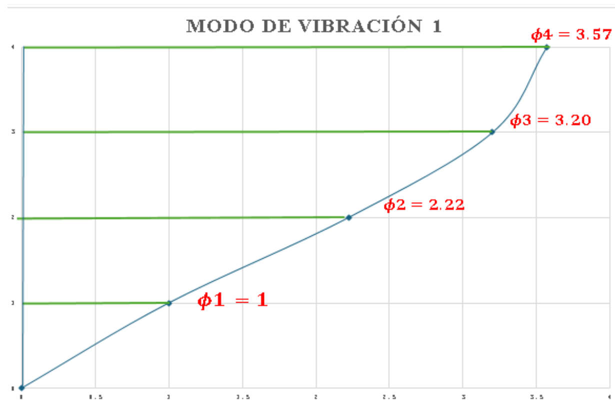
Vibration modes

With modal seismic analysis, the modes of vibration are identified and analyzed to study how the structure will respond to different types of seismic movements.

Vibration mode 1

$$\phi 1 = \begin{bmatrix} 41620 & -18709 & 0 & 0 \\ -18709 & 34032 & -17870 & 0 \\ 0 & -17870 & 39890 & -24528 \\ 0 & 0 & -24528 & 21984 \end{bmatrix}$$

Box 8

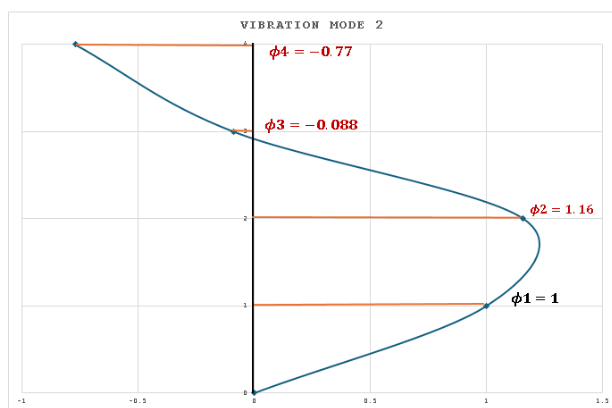


Graph 1
Vibration mode level 1
Source: Caro 2025

Vibration mode 2

$$\phi 2 = \begin{bmatrix} 21527 & -18709 & 0 & 0 \\ -18709 & 14544 & -17870 & 0 \\ 0 & -17870 & 20362 & -24528 \\ 0 & 0 & -24528 & 2826 \end{bmatrix}$$

Box 9



Graph 2
Vibration mode 2
Source: Caro, 2025

Vibration mode 3

$$\phi 3 = \begin{bmatrix} -6772 & -18709 & 0 & 0 \\ -18709 & -12904 & -17870 & 0 \\ 0 & -17870 & -7082 & -24528 \\ 0 & 0 & -24528 & -24207 \end{bmatrix}$$

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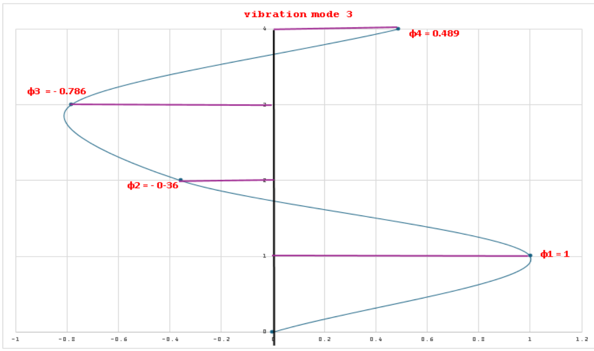
Box 10



Graph 3
Vibration mode 3

Source: Caro 2025

Conclusions

This research shows us that Manzanillo, Colima, faces a high level of seismic risk, but above all vulnerability to the liquefaction phenomenon, due to several factors including its geographical location since the port is located on the Pacific Ocean coast, as well as its interaction with the Cocos and North American tectonic plates.

It is utmost importance to continue disseminating research in seismic analysis, since earthquakes particularly in Manzanillo, have caused significant damage to the infrastructure, affecting the port economy and endangering the low-income population, since a large percentage of them live in high-risk areas.

Comply with the regulations and specifications on structural safety and design for earthquakes, assures us a better response capacity to seismic events, in order to safeguard the safety of its inhabitants, as previously mentioned.

Seismic analysis together with the review of construction regulations and wave propagations models, has allowed us to visualize the response capacity of buildings during an earthquake, which has allowed us to obtain additional forces or deformations that are generated as a result of an earthquake, such as what happened in the cities of Myanmar and Bangkok.

Therefore, recommends an optimization of structural materials in terms of analysis and design, as well as training of the population in safety protocols, both are key strategies to reduce the impacts of seismic events in the future.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

Author contribution

Caro-Becerra, Juan Luis: His contribution has been fundamental in the development of the article, it is worth mentioning that it is not the area of his research, but nevertheless, he documented with great richness both technically and scientifically, with a social sensitivity of how vulnerable we are, the beings of this planet.

Martinez-Hernández, Wilfrido: His contribution has been without any doubt in the structural design as far as the drawing in CAD format, in addition he ran the project data in the PRODISIS software [Seismic Design Program], to determine both the design spectra and the vibration modes. Criteria contained in the Civil Works Design Manual-Seismic Design CFE-IIE Version 2015.

Mayoral-Ruiz, Pedro Alonso: Without a doubt, Mr. Mayoral is the main author, his experience in soil mechanics and geotechnical engineering for the company "Soils and Control" for more than 30 years, as one of the most recognized in Guadalajara and experts on the subject, he has published articles on the phenomenon of liquefaction in the port of Manzanillo. I proposed him to write an article on the subject and he accepted my invitation.

Hernández-Magdaleno, Alfonso Manuel. He Contributed to the final draft of the article, before submitting it for review to the Scientific Committee of the 10th CIERMMI Congress. He also sponsored the article with funds from his Department of Basic Sciences at the University of Guadalajara.

Availability of data and materials

The results were obtained with quantitative methods, such as those mentioned in this article: Newmark, Holzer, Wilbur, NTC-CDMX, E.030 and those mentioned by the regulations Norms and Specifications, for Studies, Projects, Construction and Installations, vol. 4 Structural Safety, num. 2 Seismic Design.

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Many thanks to all my department and division head for encouraging us to be quality scientists.

Abbreviations

EBF Eccentrically Braced Ordinary Portal Frames
GDL Degrees of Freedom
IMF Special Resisting Intermediate Frames
OCBF Concentrically Braced Ordinary Portal Frames
OMF Ordinary Moment Resisting Portal Frames
SMF Special Moment Resisting Gantries
SCBF Concentrically Braced Special Frames

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Mechanical behavior of sustainable concrete; case study of low substitutions of fine plastic as aggregate

Comportamiento mecánico de concreto sustentable; caso de estudio sustituciones bajas de plástico fino como agregado

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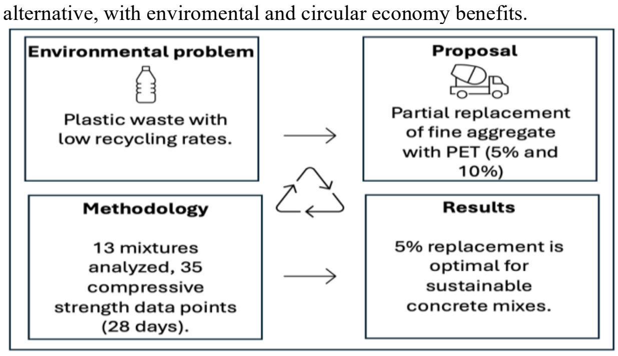
Abstract

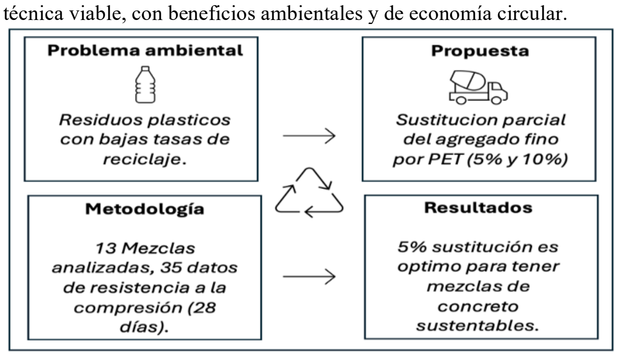
This study analyzes the mechanical behavior of sustainable concrete when incorporating recycled polyethylene terephthalate [PET] as a partial replacement for fine aggregate. Articles reporting mixtures with 5% and 10% replacements were reviewed. A total of thirteen mixtures and thyrty-five 28-day compressive strength data points were collected and compared with control mixtures. The statistical analysis included measures of central tendency, dispersion, and percentage variation, wich allowed for the normalization of result between different studies. The findings show that the 5% replacement has an average variation of -2.6%, indicating a minimal impact on strength, while the 10% replacement reports an average reduction of -11.9%. Although variability was observed, fine-grained PET favored compactness and mechanical performance. These results consolidate 5% as a viable technical alternative, with enviromental and circular economy benefits.



Sustainable Concrete, Recycled PET, Polyethylene Terephthalate, Mechanical Properties.

Resumen

Este estudio analiza el comportamiento mecánico del concreto sustentable al incorporar tereftalato de polietileno reciclado [PET] como sustitución parcial del agregado fino. Se revisaron artículos que reportan mezclas con reemplazos de 5% y 10%. En total se recopilaron trece mezclas y treinta y cinco datos de resistencia a la compresión a 28 días, comparados con mezclas control. El análisis estadístico incluyó medidas de tendencia central, dispersión y variación porcentual, lo que permitió normalizar resultados entre diferentes estudios. Los hallazgos muestran que el 5% de sustitución presenta una variación promedio de -2.6%, indicando un impacto mínimo en la resistencia, mientras que el 10% reporta una reducción media de -11.9%. Aunque se observó variabilidad, el PET de granulometría fina favoreció la compacidad y el desempeño mecánico. Estos resultados consolidan al 5% como una alternativa técnica viable, con beneficios ambientales y de economía circular.



Concreto sustentable, PET Reciclado, Tereftalato de Polietileno, Propiedades Mecanica

Area: Advocacy and attention to national problems

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Introduction

In recent decades, the increase in plastic waste has been a global concern due to its low biodegradability, excessive accumulation in landfills, and negative impact on terrestrial and marine ecosystems. It is estimated that since the 1950s, more than 8.3 billion tons of plastic have been produced, of which about 79% has ended up in landfills or scattered in the environment [Geyer et al., 2017]. Polyethylene terephthalate [PET] is commonly used in the production of bottles and packaging. It is also the most widely produced polymer and the least reused, which has led to the search for strategies for its incorporation into construction materials such as hydraulic concrete.

Concrete is the most widely used material in the world after water [Mehta & Monteiro, 2014]. It is used in most infrastructure, and its intensive production involves large volumes of non-renewable raw materials such as sand, gravel, and cement, which generate a significant environmental impact, mainly in terms of CO_2 emissions and depletion of natural resources [Habert et al., 2020]. As a result, the construction industry has begun to adopt more sustainable practices aimed at reusing waste in the production of concrete with recycled aggregates [Pacheco-Torgal et al., 2013]

Currently, the environmental problem caused by plastic waste is one of the main global challenges. It is estimated that approximately 300 million tons of plastic waste are generated each year, of which only 9% is recycled [Ocampo & Santa Catarina, 2019]. This low recycling rate poses a serious environmental risk, as this waste occupies a considerable volume and remains in the environment for decades.

In Mexico, the same study reports that 1,951,785 kg of plastic waste is generated daily, a significant amount that could be used in various recycling applications, such as the sustainable construction sector. A large part of this waste is not utilized due to the absence of efficient management and collection systems, which is further compounded by a lack of culture in the responsible handling of this material.

Plastic pollution in coastal and marine ecosystems represents a growing threat in Mexico.

According to the Ocean Conservancy [2019], at least 76% of the waste collected during coastal cleanups carried out in the country in 2009 was plastic, equivalent to approximately 8 out of every 10 pieces of waste found on beaches and in marine areas. This reflects the magnitude of the problem and highlights the urgent need to establish effective strategies for the management and reduction of plastic waste in coastal areas.

A representative case of this problem can be seen in the Gulf of California, near the region of Mexicali, Baja California, where Mijares-Mastretta [2012] warns that in order to improve the use of plastic waste, legal actions and active social participation must be implemented, encouraging the recycling of plastic containers, the accumulation of which has had harmful effects on the marine ecosystem.

Among the main consequences, the presence of microplastics in marine sediments has been documented, which poses a direct threat to wildlife. Moore et al. [2001] point out that microplastics are often ingested by marine organisms when mistaken for food, which can lead to intestinal blockages, malnutrition, or death by strangulation, thus critically affecting the region's biodiversity. Given this situation, the Ministry of Social Development [SEDESOL] has proposed comprehensive strategies through its Strategic Plan for Solid Waste Management, aimed at improving waste collection, sorting, and utilization in the country, with special attention to vulnerable coastal and urban areas.

These actions seek to strengthen a sustainable approach to waste management and are an essential component in mitigating the environmental impacts of plastic in Mexico.

Some researchers have tried partially or totally replacing natural aggregates in concrete with plastics such as PET, High-Density Polyethylene [HDPE], Polypropylene [PP], and Polyvinyl Chloride [PVC] [Siddique et al., 2008]. PET in particular has shown promising results when incorporated as a fine or coarse aggregate, depending on its particle size, shape, and percentage of replacement. Research has documented that at moderate levels, PET can maintain and, in some cases, even improve impact energy absorption, abrasion resistance, and thermal insulation [Frigione, 2010; Saikia & De Brito, 2014].

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When high percentages are used, losses in compressive strength and internal cohesion can be observed, mainly due to low adhesion between the plastic and the cementitious matrix [Hannawi et al., 2010].

The incorporation of plastic waste such as PET in concrete manufacturing represents a strategy that can bring benefits both in terms of material performance and in reducing the environmental impact associated with construction. Some studies have shown that the controlled inclusion of fine PET can improve its behavior under stress and strain, reduce its density and thermal insulation, which is useful for infrastructure applications [Silva et al., 2022].

The surface texture of crushed PET can positively influence the concrete matrix when combined with modifying additives, helping to improve its integrity, volumetry, and crack resistance [Mannan et al., 2022]. From an environmental perspective, several authors have documented that the use of PET reduces the demand for natural aggregates and minimizes the volume of waste sent to landfills [Batayneh et al., 2007]. On the other hand, there is a lack of consensus regarding the optimal substitution percentage, as in some cases significant losses in concrete strength are reported starting at 5%, while in others specific improvements are observed even with 10% substitution [Choi et al., 2005; Marzouk et al., 2007].

Methodology

This work was developed using a quantitative approach, with a non-experimental design and descriptive statistical analysis of the data collected. The documentary argument is derived from a search of articles in the Scopus and Web of Science databases from the last 10 years, selecting those that address research on concrete that replaces fine aggregate with PET in fractions of 5% and 10% and that report compressive strength results at 28 days.

The mix design proposes the percentages by weight and density of substitution by plastic materials in accordance with the recommendations of the American Concrete Institute [ACI]. It is calculated by applying the direct percentage to the inputs required for the concrete, obtaining the weight of the replacement material in the mix.

Thirteen mixtures that met the above criteria were obtained for analysis, totaling 35 data points, which were compared graphically in reference to the control mixture [the one with 0% replacement]. Evaluated with an analysis in a table containing data extracted from the results reported in the selected articles after reading the full text, a comparative graph was created showing the trends and behaviors of the replacement percentages. Based on the analysis, the replacement percentage with the best performance was identified, with the least variation between the control mixture and the replacement, respectively, to demonstrate that using replacement materials in concrete is efficient and thus promotes recycled concrete in the construction industry and makes the sector more environmentally friendly.

Results

The compressive strength of the thirteen mixtures is presented, coded by article ID in Table 1, comparing the results according to the percentage of fine aggregate replacement by recycled PET of 5% and 10% against 0% replacement, which is the control mixture reported in each article, and serves as a reference for comparing mechanical properties.

Box 1

Table 1

"Percentage of substitution and its mechanical strength results"

ID ARTICLE	% Replacement [Resistance in MPa]		
	0%	5%	10%
15	42.8	-	38
18	22.4	19	-
		16.5	-
22	59.8	60.2	45.8
32	19.3	12.7	9.2
36	31.2	25.9	21.3
37	34.8	-	38
41	26.7	24	18
42	31	-	22.3
43	22.3	19.1	-
47	35	51	38
48	37.8	40	38.3
49	35	46.9	45.36
54	38.7	39.6	38.2

The results presented in Table 1 constitute the starting point for the comparative analysis between the different concrete mixtures with varying substitution percentages.

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This table shows the strength values obtained, which allow us to establish a technical reference against which the mechanical performance of the modified mixtures will be evaluated.

The analysis of these control mixtures is essential, as it provides a baseline parameter that allows for objective interpretation of variations in strength based on trends in mechanical behavior, and discusses their possible technical causes.

In order to make an objective comparison of the effect of substitution, we decided to determine the percentage variation of each mixture with 5% and 10% replacement relative to its respective control mixture.

This strategy allowed us to normalize the results between studies with different base strengths, making it possible to make a relative comparison without relying on the absolute strength value of the original concrete.

Equation 1 was applied to obtain the percentage variation based on the following:

$$Variation\,[\%] = \left(\frac{f'_c[PET] - f'_c[Control]}{f'_c[Control]}\right) x\ 100 \quad [1]$$

Ec.1. Percentage variation in concrete mixes

The percentage variation of the thirteen concrete mixes is presented in Table 2. The data were grouped by substitution percentage, and a descriptive statistical analysis was applied to the percentage variation results.

This includes the calculation of measures of central tendency such as the mean, median, and mode, dispersion, standard deviation, variance, coefficient of variation, and range.

This evaluation made it possible to identify not only the average impact of PET on strength, but also the consistency or dispersion of the results obtained in different studies.

Box 2

Table 2

"Percentage change"

ID ARTiCLE	% change	
	5%	10%
15	-	-11.2%
18	-15.2%	-
	-26.3%	-
22	0.7%	-23.4%
32	-34.2%	-52.3%
36	-17.0%	-31.7%
37	-	9.2%
41	-10.1%	-32.6%
42	-	-28.1%
43	-14.3%	-
47	45.7%	8.6%
48	5.8%	1.3%
49	34.0%	29.6%
54	2.3%	-1.3%

In the case of mixtures with 5% PET substitution, the percentage variation values were analyzed with respect to their respective control mixtures. The analysis yielded an average of -2.60%, suggesting that, on average, this substitution percentage does not generate a significant change in compressive strength compared to mixtures without PET or with 0% replacement. However, the dispersion of the data was considerable, so the standard deviation was calculated using Equation 2:

$$\sigma = \sqrt{\frac{1}{n-1}\Sigma(x_i - \mu)^2} \quad [2]$$

In this regard, the standard deviation yielded a value of 24.28%, while the variance was 589.74. This value suggests that the behavior of PET at 5% is highly dependent on the mixture design conditions, type of PET, particle size, and other technical factors. In addition, a variation range of 79.9% was obtained, with results ranging from reductions of around -34.2% to increases in strength of around 45.07%, as reported in article ID47.

For the 10% mixture group, applying the same statistical analysis, it was possible to identify that the average percentage variation with respect to their respective control mixtures is -11.99%, indicating that, on average, this substitution ratio caused a more marked reduction in compressive strength compared to the 5% substitution.

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While the variance was 572.21, indicating a wide dispersion but slightly less than that observed in the 5% group. The calculated coefficient of variation was 199.49%, which shows highly unstable behavior. The range of variation was 81.9%, ranging from severe losses of up to -52.3% to maximum increases of 29.6%.

The comparative analysis aims to identify a pattern of improvement, decrease, or stability in compressive strength when applying a 5% and 10% substitution.

The substitution percentages and the differences between the compressive strength results are evaluated in each of the articles by means of a technical assessment. These values are compared with the reference mixtures. Standardizing the results under the same percentage facilitates a critical evaluation of the effectiveness of the substitution on the mechanical performance of the concrete.

Box 3

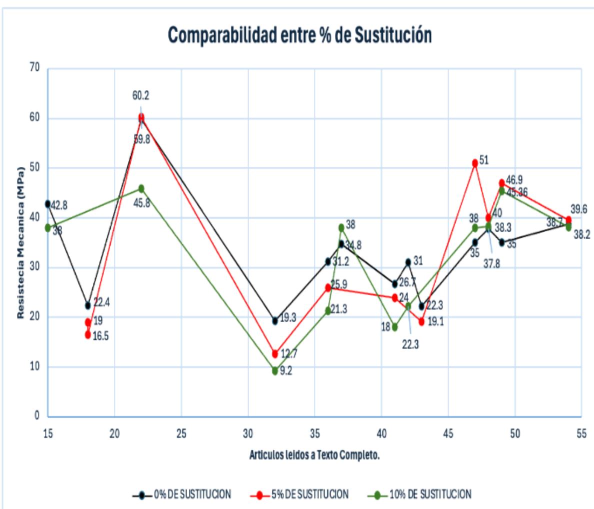

Figure 1

"Compressive strength per item and percentage of substitution"

Source: Own elaboration.

Based on Graph 1, a technical comparative analysis is performed to identify and understand the significant differences between the strength results reported in each of the articles, focusing on highlighting the most relevant variations in relation to the control mix, based on the substitution percentages previously presented and the statistical results obtained.

This influences technical factors such as mix design, cement type, water/cement ratio, curing conditions, or specific characteristics of the plastic material used, and whether they are due to particular experimental design criteria for each study. This critical review provides an answer based on the statistical analyses and the graph presented. Based on the present analysis, the aim is to establish a methodology aimed at optimizing the use of recycled plastics in concrete, which allows the results obtained to be reproduced or improved, guaranteeing both the mechanical performance and the technical and environmental viability of the material developed.

The highest and lowest resistance are identified. We can see that the item with the highest resistance is ID 22, with a resistance of 59.8 MPa for the control mixture, 60.2 MPa for a 5% substitution, and 45.8 MPa for a 10% substitution, respectively.

In this comparative analysis, it can be observed that the highest compressive strength among the selected articles was reported by Espindola-Flores et al. [2024], reaching a value of 60.2 MPa at 28 days. This is attributed to the fact that the 5% percentage allows for homogeneous dispersion of the polymeric material within the cementitious matrix, without significantly interfering with the cement hydration processes. In mixtures with higher substitution percentages, the hydrophobic nature of PET begins to negatively affect the development of the matrix [ibid.], as it reduces the effective contact between water and cementitious compounds, thus limiting the formation of calcium silicate hydrate [C-S-H] gel, which is a fundamental component for concrete strength.

In contrast, with 5% PET, the reaction and hydration of the cement can continue, which favors the formation of a denser, more compact, and more resistant structure. It contributes mechanical properties such as energy absorption, dissipating stress during load testing.

According to the analysis, Article 32 shows the most significant negative results, where flattened and rounded plastic was used as a partial substitute for fine aggregate.

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The maximum strength achieved was 12.5 MPa, while the mixture with 5% substitution obtained a strength of 12.72 MPa, exceeding the strength of the control mixture. This article highlights the use of 15% fly ash as a complementary pozzolanic material, identifying that adding this to concrete mixtures results in a minimal decrease in compressive strength compared to those without this material. What we can say is that incorporating supplementary cementitious materials such as fly ash can partially offset the negative effects of PET on cement hydration, thus increasing the strength of the concrete.

In the analyzed article of ID 47, the results show a particular behavior in compressive strength, with a significant increase in strength compared to the control concrete, registering 45.7% higher strength according to the control mixture, replacing 5% and 8.6% for 10%.

This can be explained by the laminar and flattened shape of the PET particles, which, when integrated into the cement matrix, generate a redistribution of stress in the critical areas of failure initiation. Therefore, the plastic particles act as flexible elements capable of absorbing part of the shear stress and transforming it into tensile stress.

This characteristic gives concrete additional deformation capacity before fracture, which does not occur in natural aggregates with spherical morphology and brittle behavior. Furthermore, PET, being non-porous and non-water-absorbent, prevents the formation of micro-hydration zones on its surface, reducing the appearance of weak points due to excess voids at the aggregate/mortar interface, also seen in other articles.

It should be noted that two different gradations of PET particles were used to manufacture the mixtures: the first with sizes between 2 and 4.9 mm and the second, finer, with sizes between 0.05 and 2 mm. They were previously washed using a wet screening method and then dried in the open air under direct exposure to sunlight, thus ensuring the cleanliness and uniformity of the recycled aggregates before their incorporation into the concrete mixture.

Conclusions

The 5% substitution showed an average percentage of -2.60%, indicating a slight reduction on average, while the 10% showed an average of -11.99%, representing a more considerable decrease in resistance. This finding suggests that the higher the percentage of substitution, the greater the negative impact on resistance, a trend also observed in several previous studies.

In terms of consistency between results, the analysis shows that both percentages present high dispersion, although 10% was statistically more stable; the coefficient of variation was 934.02% for 5%, compared to 199.49% for 10%, indicating that the effects of 5% are variable and less predictable between studies.

Although 10% also showed instability, its results are distributed close to its mean, as confirmed by its median of -11.2%, similar to the mean of -11.99%, compared to the more dispersed values in 5% with a mean of -2.6% and a median of -10.1%.

The range of variation was also wide in both cases, indicating that there are extreme cases in which PET substitution has led to severe losses in strength or significant improvements.

These differences are probably due to the diversity of methodologies used in the articles analyzed, such as the type of PET, particle size, mixture design, water-cement ratio, additives, and curing conditions. Statistically, 5% shows a lower average loss of strength, but its high coefficient of variation reveals high instability between studies, which limits its reliability if the mixture variables are not controlled. Ten percent tends to show a clearer reduction in strength, but its results are more statistically consistent.

Therefore, the choice between 5% or 10% as a replacement percentage should depend not only on the strength values obtained, but also on the technical control of the mixture and the acceptable level of risk in the construction project.

Based on a comparative analysis of the reviewed articles, it was found that a 5% PET replacement rate is the most favorable level for the development of plastic-modified concrete.

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This allows for homogeneous dispersion of the material within the cement matrix, preventing significant interference with the cement hydration processes and promoting the formation of a more compact and resistant microstructure.

The results obtained also show that finer PET gradation promotes significantly higher compressive strength compared to that obtained in other studies. This behavior can be attributed to the fact that the smaller particles acted as a micro-filler, improving the compaction of the cement matrix by reducing the presence of voids. Their specific surface area also promoted better mechanical anchoring with the cement paste, which increased the concrete's ability to resist compressive loads. This effect contrasts with what was reported in research, where fine PET produced lower strengths. The difference lies in the preparation method applied in that study, in which the washing and gradation control process allows for cleaner, more uniform particles with better particle size distribution.

These conditions ensured that PET did not act solely as an inert substitute but also participated in optimizing compactness and redistributing internal stresses in the mixture.

It was observed that percentages above 10% tend to decrease resistance due to the hydrophobic nature of PET and the progressive loss of cohesion at the paste-aggregate interface, which limits the mixture's ability to form a continuous and dense structure.

The outstanding performance of the 5% substitution suggests that this percentage can be replicated as a viable technical alternative for the industry, ensuring a balance between mechanical performance, plastic waste utilization, and environmental viability, directly contributing to sustainability goals by reducing the extraction of natural aggregates while adding value to a waste material with high environmental impact such as PET, favoring the reduction of pollution and promoting circular economy practices within the construction sector.

To consolidate this proposal as a large-scale solution, future research must focus on optimizing PET preparation and degradation conditions, evaluating compatibility with different types of cement and mineral additives, and exploring the behavior of the material under different environmental exposures.

In this way, progress can be made toward the design of an “optimal” mixture that combines mechanical performance, technical efficiency, and a real contribution to the sustainability of the concrete industry.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no competing financial interests or known personal relationships that could have influenced the article presented in this paper.

Authors' contribution

The contribution of each researcher to each of the points developed in this research was defined based on:

Arias Jhovanny: Led the writing of the manuscript, participated in the search and selection of articles, as well as in the extraction of experimental data reported in the literature. He performed the initial processing of the information and collaborated in the structuring of the statistical and technical analyses.

Gutierrez Manuel: Responsible for the comprehensive drafting and cohesion of the article, ensuring clarity and consistency of content. Directly involved in the validation of calculations and statistical review, verifying the accuracy of the results presented.’

Arcos-Vega José Luis: He contributed to the methodological design of the study, defining the criteria for selecting articles and the strategy for comparing mixtures. He also reviewed the entire document, proposing technical and methodological adjustments to strengthen its academic rigor.

Calderón, Julio: He contributed to the writing of specific sections of the manuscript and was responsible for preparing the tables and graphs for the comparative diagrams representing the results. He also participated in the technical review of the visual presentation of the data.

Availability of data and materials

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Abbreviations

ACI	American Concrete Institute
ANN	Artificial Neural Network
C-S-H	Calcium Silicate Hydrate
FA	Fly Ash
HDPE	High-Density Polyethylene
MPa	Megapascal
PET	Polyethylene Terephthalate
PP	Polypropylene
PVC	Polyvinyl Chloride
w/c	Water–Cement Ratio
%	Percent

ACI	American Concrete Institute
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Article

Digital reconstruction of historical monuments with drones and 3D Photogrammetry: An ICT application for heritage management

Reconstrucción digital de monumentos históricos con drones y fotogrametría 3D: Una Aplicación de TICs para la gestión del patrimonio

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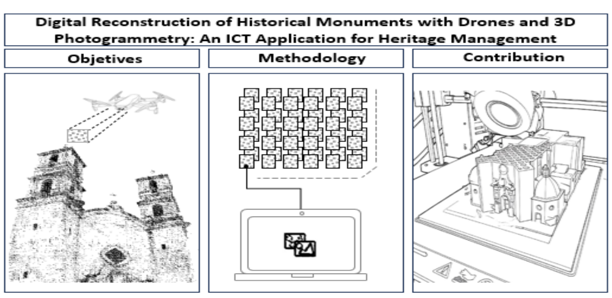
Abstract

This study presents a technological alternative for the digital representation of historical buildings, leveraging drones and aerial photogrammetry. The research was conducted on the Parish of San Jerónimo, located in Huandacareo, Michoacán, to construct a detailed three-dimensional model to support structural analysis and heritage documentation. The methodological process included flight path planning, systematic image acquisition using a DJI Mini 2 SE drone, and subsequent processing in Agisoft Metashape. This workflow enabled the generation of accurate 3D models derived from point clouds and digital meshes. The resulting model was validated by comparing its dimensions with real-world measurements, achieving high fidelity with a maximum deviation of ±0.15 cm per meter. The main contribution of this work is to demonstrate that accessible technological tools can effectively support the conservation and documentation of heritage structures, while reducing costs and minimising fieldwork risks.



Drone, 3D modelling, Photogrammetry.

Resumen

Este trabajo presenta una alternativa tecnológica para la representación digital de edificaciones históricas mediante la implementación de drones y técnicas de fotogrametría aérea. El estudio se desarrolló en torno a la Parroquia de San Jerónimo, ubicada en Huandacareo, Michoacán, para elaborar un modelo tridimensional que permita el análisis estructural y el registro patrimonial. El proceso metodológico incluyó la planificación de rutas de vuelo, la captura sistemática de imágenes con un dron DJI Mini 2 SE y su posterior procesamiento en la plataforma Agisoft Metashape, para generar modelos 3D precisos a partir de nubes de puntos y mallas digitales. La evaluación del modelo generado se validó contrastándolo con las dimensiones de mediciones reales. El resultado fue un modelo de alta fidelidad, con una variación máxima de ±0.15 cm por metro. La herramienta tecnológica apoya eficazmente la documentación de construcciones patrimoniales, reduciendo costos y riesgos asociados al trabajo de campo.

Dron, Modelado 3D, Fotogrametría.

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

Safeguarding historical monuments is not only a technical challenge but also a cultural responsibility, as these sites carry society's memory, identity, and traditions. In Mexico, their preservation is overseen by the National Institute of Anthropology and History [INAH] through the National Coordination of Historical Monuments [CNMH].

According to the Federal Law on Archaeological, Artistic and Historical Monuments and Zones, any intervention in these buildings must be authorised and supervised by the INAH to guarantee their conservation. While this regulatory framework establishes the basis for protection, it also highlights the need for innovative methods to document and analyse heritage in efficient, accurate, and non-invasive ways.

Recent advances in information and communication technologies have introduced new possibilities for heritage management. Among them, drones combined with aerial photogrammetry stand out as a versatile alternative to traditional surveying techniques. Unlike conventional approaches, which often require significant resources and may even put fragile structures at risk, drone-based photogrammetry enables rapid data collection, high-resolution imagery, and the creation of reliable 3D models. These models offer more than visual records; they provide measurable information that can support structural assessments, help track deterioration over time, and preserve digital evidence for future restoration projects.

The problem this study addresses is the limited availability of methodologies that are both accessible and precise for the systematic documentation of historical buildings. Traditional practices can be slow, expensive, or difficult to replicate across different contexts.

This research proposes that integrating drones with photogrammetric techniques can fill that gap by delivering accurate 3D reconstructions validated against on-site measurements.

The central hypothesis is that this approach can strengthen both the technical evaluation and the cultural safeguarding of heritage monuments.

Rather than presenting the study as a set of rigid sections, it is worth noting that this work begins with a brief discussion of the background and theoretical principles that frame the use of drones and photogrammetry in heritage conservation. It then moves into the methodological approach applied to the San Jerónimo Parish in Huandacareo, where the combination of aerial imagery and digital processing was put into practice.

The results obtained from this case illustrate not only the accuracy of the 3D reconstruction but also its potential to support preservation strategies. From there, the discussion naturally opens up to the advantages and challenges of adopting these technologies, leading to broader reflections on how digital tools may shape the future of cultural heritage management.

Methodology

The methodological design of this research integrates aerial photogrammetry and drone technology to achieve precise three-dimensional documentation of historical monuments. The process begins with identifying key variables that directly influence the quality of the photogrammetric model: flight altitude, ground sample distance [GSD], image overlap, camera resolution, and the number and distribution of ground control points [GCPs]. Each of these factors has been widely recognised in recent studies as decisive for ensuring the geometric accuracy of digital reconstructions [Bolognesi, 2023], [Hinge, 2019].

The first stage involved planning the flight mission, during which the DJI Mini 2 SE was configured to operate at a safe, consistent altitude. Parameters such as speed, orbital patterns, and photo-capture intervals were adjusted to ensure systematic coverage of San Jerónimo Parish [Figure 1]. The advantage of using drones lies in their ability to access complex angles and minimise risks to operators, compared with traditional scaffolding-based surveys or total station scanning, which can be more invasive and less efficient [Carvajal-Ramírez, 2019].

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Box 1

[a]

[b]

Figure 1
Perspectives of modelled architecture
Source: Own work

Once the flight plan was executed, the images were collected with careful attention to overlap [front: 80%; side: 70%], as recommended in recent guidelines for heritage documentation [Zhang, 2025]. The dataset was then processed in Agisoft Metashape, with the workflow including photo alignment, dense point cloud generation, mesh reconstruction, and texturing. The digital model was georeferenced using ground control points to ensure consistency with real-world coordinates.

A critical step in this methodology was comparing the reconstructed model with actual field measurements. This validation, performed using on-site physical dimensions, confirmed the accuracy of the 3D model to within ±0.15 cm per meter. Such precision demonstrates the reliability of photogrammetry as an alternative to laser scanning, which, although highly accurate, often entails higher costs and specialised equipment [Zakaria, 2025].

The methodological approach adopted here not only emphasises the technical rigour of data acquisition and processing but also highlights its replicability. By combining accessible drone technology with advanced photogrammetric software, this study proposes a sustainable framework that cultural institutions can replicate for the documentation and conservation of heritage sites.

Results

The case study focused on the Parish of San Jerónimo in Huandacareo, Michoacán, where more than 800 aerial photographs were captured using a DJI Mini 2 SE drone.

These images provided the raw dataset for photogrammetric processing. The flight plan ensured systematic coverage with adequate overlap, allowing for precise reconstruction of the building's geometry. This stage alone demonstrated the potential of drones to document historical sites without exposing them to physical risks, an advantage over conventional surveying techniques [Bagnolo, 2019].

The collected images were processed in Agisoft Metashape, where alignment, dense point cloud generation, and mesh reconstruction were performed.

Box 2

Figure 2
Start of image construction in Agisoft Metashape.
Source: Own work

The software enabled the extraction of geometric and textural information, producing a highly detailed digital twin of the monument.

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This process required several hours of computational work, yielding a scalable 3D dataset that could be reused for diverse applications, from conservation to virtual dissemination [Wahbeh, 2017].

Around the object, extraneous elements were identified; therefore, the scene was refined to prevent these parts from being processed and incorporated into the 3D model. For this task, the freeform selection tool was employed as shown in Figure 3.

Box 3

Figure 3
Construction of the 3D model.
Source: Own work

To assess the model's reliability, the dimensions derived from the 3D reconstruction were compared with field measurements. The analysis confirmed a mean accuracy of ±0.15 cm/m, consistent with international standards for architectural photogrammetry. Subsequently, the building was printed as shown in Figure 4.

Box 3

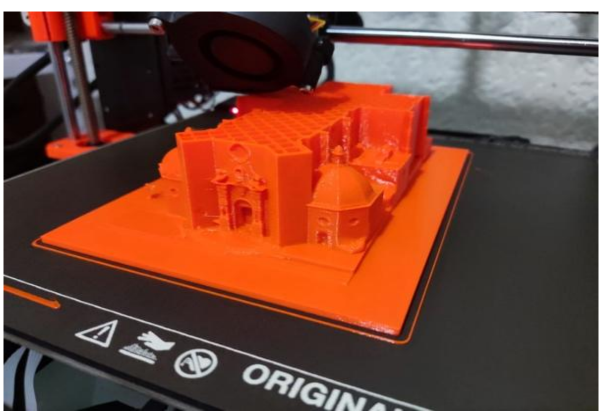

Figure 3
3D printing process.
Source: Own work

This degree of precision highlights the capacity of UAV-based photogrammetry to serve as a viable alternative to terrestrial laser scanning, while maintaining lower costs and easier deployment [Zakaria, 2025].

The resulting 3D model of the Parish not only documents the building's current condition but also serves as a reference for preventive conservation. Stored in digital repositories, the images and models enable periodic comparisons to monitor deterioration, evaluate previous restoration works, and plan new interventions.

Beyond technical documentation, the digital twin also supports educational and outreach initiatives by enabling communities and institutions to visualise and interact with cultural heritage in new ways [Hermon, 2022].

Conclusions

a. This research demonstrated that drone-based photogrammetry is not only a viable tool for documenting historical monuments but also a transformative approach that redefines how heritage inspections are carried out. Traditionally, assessing buildings such as the San Jerónimo Parish required manual surveys, scaffolding, or direct physical access to fragile structures—methods that were often time-consuming and expensive and posed significant safety risks to inspectors. By contrast, the methodology presented here enabled the generation of a highly accurate 3D model, validated to ±0.15 cm per meter, without exposing personnel to hazardous conditions.

b. The impact of this approach is twofold. On the one hand, it provides cultural institutions, such as the National Institute of Anthropology and History [INAH], with reliable digital records that support preventive conservation, restoration planning, and long-term monitoring of deterioration. On the other hand, it democratises access to technology, showing that even with affordable drones and accessible software, it is possible to achieve results comparable to those from more expensive, specialised equipment. This not only reduces costs but also makes the methodology replicable for smaller municipalities and communities seeking to safeguard their cultural heritage.

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c. Nevertheless, there is room for improvement. Future research should explore integrating photogrammetry with Building Information Modelling [BIM] systems and artificial intelligence algorithms to detect cracks, deformations, or material decay automatically. In addition, combining drone imagery with thermal or multispectral sensors could provide deeper insights into structural health beyond what the human eye can see.

d. In essence, this study shows that what was once a rudimentary and risky task can now be performed with precision, safety, and efficiency. By embracing technology, heritage management shifts from a reactive process to a proactive, preventive strategy, ensuring that monuments like San Jerónimo Parish are preserved, understood and appreciated for their full historical and cultural significance.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Vega-Flores, María Yaneth, Sánchez-Hernández, Miriam Zulma and Téllez-Martínez, Jorge Sergio: Contributed to the project idea, research method and technique.

Fernández-Flores Víctor Delfino: He was responsible for the project.

Availability of data and materials

The data obtained and the materials used for the modelling form are the property of the cultural conservation institutions; therefore, they are not available to any particular external interest.

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Abbreviations

INAH National Institute of Anthropology and History
CNMH National Coordination of Historical Monuments
GSD Ground Sample Distance
GCP Ground Control Points
UAV Unmanned Aerial Vehicle
BIM Building Information Modelling

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Antecedents

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Development and application of a natural waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica] in sustainable restoration materials for the conservation of built heritage [vernacular architecture]: case study of the Mezquital Valley, Hidalgo

Desarrollo y aplicación de un impermeabilizante natural a base de mucílago de nopal [Opuntia ficus-indica] en materiales restauradores sostenibles para la conservación del patrimonio edificado [arquitectura vernácula]: caso de estudio Valle del Mezquital, Hidalgo

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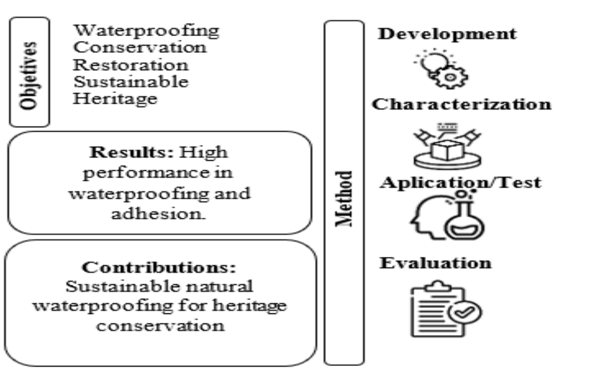
Abstract

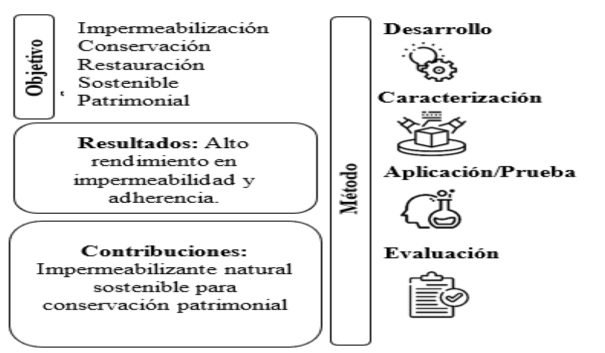
The conservation of built heritage requires the use of compatible, efficient, and sustainable materials. This study develops and applies a natural waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica], intended for sustainable restoration materials. Its adhesion capacity, moisture retention, and compatibility with traditional materials were evaluated through experimental tests and controlled applications. The results show that nopal mucilage performs well in terms of water absorption, constituting an ecological, economical, and effective alternative to conventional synthetic products, contributing to heritage conservation and promoting environmentally friendly restoration practices.



Sustainability, Transdisciplinarity, Resilience

Resumen

La conservación del patrimonio edificado requiere el uso de materiales compatibles, eficientes y sostenibles. Este estudio desarrolla y aplica un impermeabilizante natural a base de mucílago de nopal [Opuntia ficus-indica], destinado a materiales restauradores sostenibles. Se evaluó su capacidad de adherencia, retención de humedad y compatibilidad con materiales tradicionales mediante ensayos experimentales y aplicaciones controladas. Los resultados muestran que el mucílago de nopal ofrece un buen desempeño frente a la absorción de agua, constituyendo una alternativa ecológica, económica y eficaz frente a productos sintéticos convencionales, contribuyendo a la conservación del patrimonio y fomentando prácticas de restauración respetuosas con el medio ambiente.



Sustentabilidad, Transdisciplinaridad, Resiliencia

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

The preservation of architectural heritage requires restoration materials that ensure physical-chemical compatibility, functional performance, and environmental sustainability [D'Agostino *et al.,* 2023]. Historically, the waterproofing agents and additives used in restoration have been synthetic, effective but capable of altering the breathability and hygroscopic balance of ancient materials, causing internal stresses, moisture retention and premature degradation [D'Agostino *et al*., 2023].

Therefore, the exploration of ecological options that are in harmony with traditional construction systems is emerging as a key focus of research for experts in conservation and materials science. Mucilage obtained from Opuntia ficus-indica, an abundant and renewable natural polysaccharide, stands out as a promising biopolymer for enhancing the functional characteristics of cements and mortars, acting as a bioadditive and water retainer without damaging the original porosity or microstructure [Cerchas *et al*., 2024]. Recent research confirms that this mucilage increases the consistency and strength of cement mixtures, preserving or optimising critical aspects such as water absorption and porosity, without adverse long-term impacts [Cerchas *et al*., 2024]. Thus, nopal mucilage emerges as a viable alternative to traditional synthetic additives, with environmental and economic advantages due to its biological origin and local accessibility.

Beyond structural uses, O. ficus-indica mucilage has been tested in cultural heritage conservation, where its adhesive qualities, water retention and biopolymer film formation make it a protective coating that respects the vapour permeability and hygroscopic behaviour of historical materials, without altering their intrinsic properties [D'Agostino *et al*., 2023]. This work is based on the hypothesis that a natural waterproofing agent based on Opuntia ficus-indica mucilage represents an effective, cost-effective and environmentally friendly solution for reinforcing the moisture resistance of sustainable restoration materials, without compromising their compatibility with traditional constructions. It is proposed that this strategy not only mitigates capillary absorption and water infiltration, but also promotes more environmentally friendly restoration practices in line with preventive conservation.

The article is structured as follows: initially, the state of the art on vernacular architecture in the Mezquital Valley is reviewed. Next, the experimental methodology for its extraction and application in restoration materials is detailed, along with tests to measure its response to moisture.

The results and their analysis evaluate adhesion, water retention, and resistance to moisture absorption. Finally, the conclusions address the implications for heritage conservation and suggest future avenues of research in sustainable restoration.

State of the Art: Vernacular Architecture in the Mezquital Valley, Hidalgo

Vernacular architecture in Mexico has been addressed in recent literature as a cultural and constructive manifestation closely linked to the territory, local knowledge and the availability of materials, consolidating itself as a fundamental component of the built heritage and cultural landscape. In the case of the Mezquital Valley, Hidalgo, research highlights that indigenous communities, particularly the Otomí, have developed construction systems adapted to semi-arid climatic conditions, using local materials such as earth, stone and plant resources, including maguey, which demonstrates a direct relationship between the environment, cultural identity and traditional architectural practices [Argüello & Enríquez de los Ríos, 2022].

These studies indicate that vernacular architecture not only fulfils housing functions, but also incorporates social and symbolic values, while facing processes of transformation derived from modernisation, migration and the introduction of industrialised materials.

At the state level, recent research has identified a progressive transition from vernacular architecture to contemporary self-construction processes in various regions of Hidalgo, which has given rise to hybrid built landscapes that combine traditional techniques with modern solutions, generating tensions between heritage conservation and the satisfaction of new social needs [García *et al.,* 2023].

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From a broader theoretical perspective, contemporary literature agrees that vernacular architecture should be understood as a dynamic and living phenomenon, whose conservation requires comprehensive approaches that recognise both its cultural value and its environmental potential and contribution to strategies for sustainability and conservation of the built heritage and cultural landscape [Martínez & Ávila, 2024; Urquijo, 2025].

Traditional materials and construction strategies for protection against rain in the vernacular architecture of the Mezquital Valley, Hidalgo

In the Mezquital Valley region of Hidalgo, traditional vernacular architecture is characterised by the use of local and natural materials that respond both to semi-arid climatic conditions and to the ancestral knowledge of the Hñähñu communities, being a fundamental component of the region's built heritage.

Among the predominant materials are earthen constructions, such as adobe walls and earthen structures with plant reinforcements, which take advantage of thermal mass and the availability of local resources to achieve interior comfort without complex industrial processes [Argüello & Enríquez de los Ríos, 2022].

Likewise, natural stone continues to play an important role in vernacular buildings in the valley, especially in the walls and foundations of Hñähñu constructions, where masonry techniques reflect a long tradition of adaptation to the local biocultural environment and have a high heritage value, although they are at risk of disappearing due to the loss of associated practices and knowledge [Velázquez & Guerrero, 2023]. Wood has also been traditionally used for structural elements such as beams and roofs, integrated with mixed techniques that harmonise stability and construction flexibility [García *et al*., 2023].

These materials not only represent functional and sustainable solutions, but also embody the technical and cultural knowledge of the Otomí-Hñähñu communities, highlighting the need for their documentation and conservation in the face of increasing replacement by industrialised materials that lose the original characteristics of vernacular architecture [Velázquez & Guerrero, 2023].

In the vernacular architecture of the Mezquital Valley, Hidalgo, protection from rain is achieved mainly through a combination of materials and construction techniques, as traditional adobe or rammed earth walls are not completely waterproof. For roofs, fired clay tiles are used, which, because they are fired, offer resistance to moisture and, when installed on sloping roofs with extended eaves, prevent leaks and protect the walls from erosion by rain [Velázquez & Guerrero, 2023].

In addition, coatings of clay mixed with lime or other natural stabilisers are used, which reduce water absorption and increase the durability of the walls, while maintaining their breathability [Argüello & Enríquez de los Ríos, 2022]. At the base of the walls, stone plinths act as a barrier against rising damp and rain splashes, while overlapping plant coverings, such as reed or palm, partially protect the roofs from light rain, especially in older buildings. In recent times, some homes have incorporated metal sheets or fibre cement as waterproof coverings, increasing resistance to rain, although these solutions are not part of the original vernacular tradition [García *et al*., 2023]. Taken together, these strategies show that waterproofing in the valley's architecture does not depend on a single material, but rather on the harmony between techniques, construction methods, and the intelligent use of local resources, adapted to the region's semi-arid climate.

Methodology

Stage 1: Procedure for extracting mucilage from prickly pear [*Opuntia ficus-indica*]

The extraction of mucilage from Opuntia ficus-indica began with the selection of an authorised cultivation area in the municipality of Ixmiquilpan, Hidalgo, avoiding protected areas where the extraction of cacti is restricted. Semi-mature pads, approximately two to three years old, which were not suitable for commercial consumption, were collected, ensuring the use of waste material.

The selected pads were carefully cut with a knife, avoiding injury from thorns, and transferred to suitable containers. In the laboratory, the samples were cleaned and peeled, removing surface and deep thorns, as well as part of the epidermis, in order to obtain clean and homogeneous nopal tissue for mucilage extraction.

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The pads were then cut into julienne strips and then into small cubes, increasing the surface area in contact with water to promote the release of mucilage. The nopal fragments were placed in clean containers, to which 2 litres of purified water were added for every four medium-sized pads, allowing the system to rest for three days at room temperature, facilitating the diffusion of the mucilage from the tissue into the water.

Finally, the liquid mucilage was separated from the solid material by filtration through a fine sieve and stored in sterilised, sealed and labelled glass jars for preservation, ensuring the integrity and stability of the product for subsequent experimental applications.

Box 1

Figure 1
Extraction of mucilage from prickly pear [Opuntia ficus-indica]
Source: Own elaboration

Stage 2: Preparation of waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica]

The following is a list of the materials used to manufacture the waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica].

Materials
Neutral soap
Alum stone
Lime stone
Water
Nopal mucilage [Opuntia ficus-indica]

Laboratory tools and materials
1 1000 ml test tube
1 25 ml test tube
1 mortar
1 scalpel
1 1 litre beaker
1 thermometer
1 spatula

Box 2
Table 1
Material proportions

Material	Ratio
Neutral soap	15 g
Alum stone	40 g
Water	400 ml
Nopal mucilage	70 ml

Source: Own elaboration

The procedure for preparing the natural waterproofing agent based on nopal [Opuntia ficus-indica] mucilage began with the preparation of the solid materials, including the dosing and grinding of the soap, alum stone and lime stone. Next, two volumes of water were heated in beakers, 460 ml in one and 400 ml in the other, almost to boiling point. The alum stone was dissolved in the first beaker, while the lime and soap were gradually added to the second, avoiding the formation of lumps.

Once the substances had dissolved, the solutions were left to cool and stored separately to prevent unwanted reactions. Finally, the nopal mucilage was added to the jar containing the lime and soap and mixed until a homogeneous solution was obtained, ready for use as a waterproofing agent.

Box 3

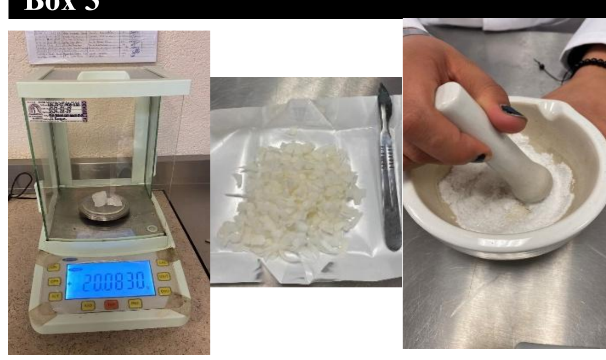

Figure 2
Dosing and grinding of materials
Source: Own elaboration

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Box 4

Figure 3
Preparation of natural waterproofing agent based on nopal [Opuntia ficus-indica] mucilage
Source: Own elaboration

Stage 3: Adobe manufacturing

The adobe bricks were made using a controlled process, starting with the selection of the constituent materials, using clay soil as the main matrix and dry plant fibres as reinforcement. The soil was first crushed and tamped to remove lumps and coarse particles, ensuring a uniform grain size and free of rigid inclusions. Water was then gradually added until a homogeneous and cohesive paste was obtained, to which the plant fibres were added, ensuring uniform distribution and a malleable but structurally stable consistency.

This mixture was shaped into blocks using wooden formwork, ensuring adequate compaction to minimise internal voids and levelling the surface with wooden instruments to obtain flat finishes. Once the formwork was removed, the adobe bricks were subjected to controlled drying in the shade for one or two weeks, which allowed the moisture to evaporate gradually and prevented the appearance of cracks, thus ensuring its mechanical strength and durability, suitable for use in construction or in the restoration of built heritage.

Box 5

Figure 4
Adobe block manufacturing process
Source: Own elaboration

Stage 4: Determination of water absorption capacity in adobe

To determine the water absorption capacity of adobe, controlled laboratory tests were carried out. Initially, a sample of adobe was placed on a suitable surface that allowed the progress of water filtration to be clearly observed. Subsequently, a 20 ml syringe was used to gradually deposit water on the upper surface of the sample, controlling the flow evenly.

During the process, the time it took for the water to be absorbed and filtered through the material was recorded, allowing for a quantitative assessment of the adobe's permeability and its behaviour in response to moisture.

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Box 6

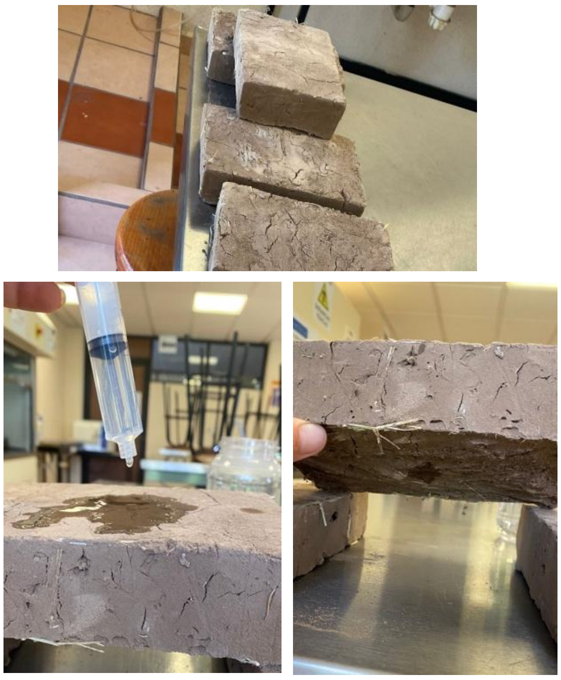

Figure 5
Determination of water absorption capacity in adobe
Source: Own elaboration

Stage 5: Application of waterproofing to adobe blocks.

The natural waterproofing agent made from nopal cactus mucilage was applied to the surface of the adobe samples in an even layer, ensuring that the material was completely covered to guarantee its effectiveness. Once applied, it was left to rest for 3 to 4 hours to allow the active components of the mucilage to adhere to the substrate and form a film that promotes waterproofing.

Box 7

Figure 6
Application of waterproofing agent on adobe blocks
Source: Own elaboration

Stage 6: Determination of water permeability in adobe samples waterproofed with nopal mucilage [Opuntia ficus – indica]

Subsequently, the samples underwent permeability testing, evaluating water absorption on the treated surface and thus verifying the mucilage's capacity as a natural agent for protection against moisture.

Box 8

Figure 7
Evaluation of permeability in adobe blocks waterproofed with nopal cactus mucilage [Opuntia ficus-indica]
Source: Own elaboration

Results

The study confirmed that Opuntia ficus-indica mucilage acts as an effective natural waterproofing agent for adobe, a material widely used in the vernacular architecture of the Mezquital Valley in Hidalgo.

The results showed that its application reduces water absorption and infiltration rates without completely sealing the pores or affecting the breathability and hygroscopic balance of the material. The process of extracting the mucilage and preparing the waterproofing agent was carried out using simple, low-cost techniques with low environmental impact, obtaining a homogeneous and stable solution.

Application to the adobe blocks produced a uniform film with good adhesion, improving moisture resistance compared to untreated samples. Taken together, the findings show that the use of nopal mucilage represents a sustainable, compatible and suitable alternative for the protection and conservation of traditional materials in the field of architectural heritage.

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Conclusions

The study concluded that Opuntia ficus-indica mucilage is a viable natural waterproofing agent for application to adobe, as it effectively improves the material's resistance to moisture without compromising its porosity or breathability, which are essential characteristics in vernacular architecture. The methodology for extracting and preparing the waterproofing agent was simple, accessible and had a low environmental impact, which favours its possible application in rural contexts and heritage conservation projects.

The tests showed that the treated adobe blocks had lower water absorption and permeability compared to those without treatment, confirming the effectiveness of the mucilage as a protective agent. Overall, the results support the use of this biopolymer as a sustainable and compatible alternative to synthetic waterproofing agents, contributing to the conservation of traditional architectural heritage and promoting restoration practices in line with the cultural and environmental context.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this paper.

Author contributions

ABR and JCRU conceptualisation and methodology; JCRU and ZBTT validation and writing; MBA review.

Availability of data and materials

All material and data will be available for consultation upon direct request to the corresponding author, subject to applicable ethical restrictions.

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Background

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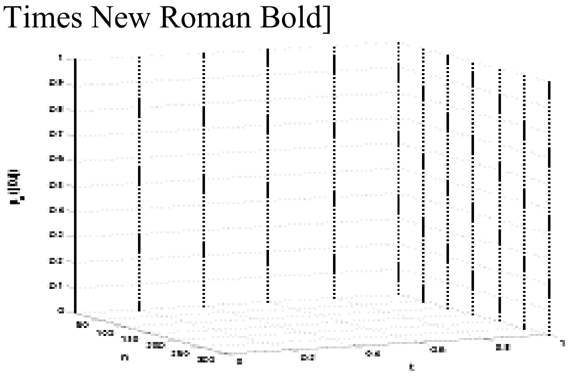

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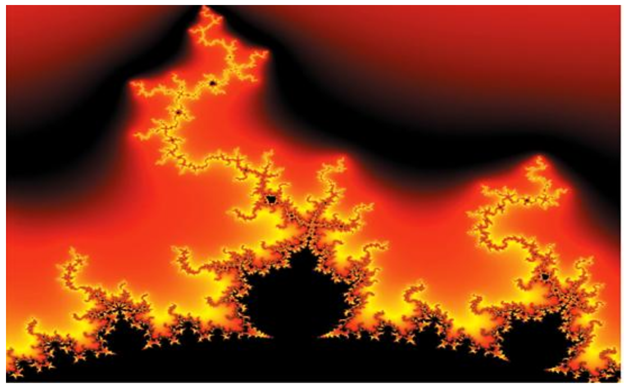

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