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Lattice design made with recycled polymeric concrete for the facade of a single-family house

Diseño de celosía hecha con concreto polimérico reciclado para fachada de vivienda unifamiliar

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Abstract

There has been an increase in the generation of urban solid waste and special handling waste in Mexico in recent years; today there are not enough final disposal sites to dispose of the waste that is generated. Urgent measures that reduce the number of waste that enters these sites through proper reuse and recycling. For this reason, this article shows how–through an appropriate recovery–materials and elements can be re-purposed for the construction of single-family homes. For this, a lattice for an exterior facade was designed from a recycled polymer concrete in order to improve the range of thermal comfort and mitigate energy consumption inside a single-family home in the municipality of Cuautla Morelos. An experimental and descriptive methodology was carried out where the elaboration of molds was carried out to later obtain the lattice and finally mechanical, thermal tests and digital simulations of the wind tunnel. Favorable results were obtained from the geometry applied to the lattice and the performance of the material in a hot climate.

Lattice, Recycled Polymeric Concrete, Facade

Resumen

Se han registrado en los últimos años un incremento en la generación de residuos sólidos urbanos y de manejo especial en México, mientras que hoy en día no se cuenta con suficientes sitios de disposición final para disponer de la basura que se genera, por lo que urgen medidas que disminuyan el número de residuos que ingresan a estos sitios a través del rehúso y recuperación apropiada de ellos. Por este motivo el presente artículo muestra como a través de un reciclaje adecuado se pueden crear materiales y elementos para la construcción en viviendas unifamiliares. Para ello, se diseñó una celosía para una fachada exterior a partir de un concreto polimérico reciclado a fin de mejorar el rango de confort térmico y mitigar el consumo energético al interior de una vivienda unifamiliar en el municipio de Cuautla Morelos. Se llevó a cabo una metodología experimental y descriptiva donde se realizó la elaboración de moldes para obtener la celosía y finalmente se hicieron pruebas mecánicas, térmicas y simulaciones digitales de túnel de viento. Se obtuvieron resultados favorables de la geometría aplicada en la celosía y el desempeño del material en un clima caluroso.

Celosía, Concreto Polimérico Reciclado, Fachada

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Introduction

In Mexico and worldwide, the number of municipal solid wastes (MSW) produced each year has increased, generated primarily at home, work, school, etc. and resulting from the disposal of products used in daily activities. This stems from the increase in population requiring more goods and services that are necessary for their daily activities.

For this reason, appropriate landfills must be available to dispose of waste, otherwise they will be places that contaminate drinking water, ecosystems and are subject to the spread of infections and diseases.

However, Mexico faces problems in the management of MSW, from its correct separation to its final disposal, since these sites have inadequate infrastructure and 65% of these sites have already concluded their useful life, 20% have more than 10 years of operation and the rest have between 1 and 5 years of proper operation (Patiño, 2022, para. 11).

This means that there are no more places to dispose of waste in Mexico today, while waste generation is increasing, so measures are urgently needed to reduce the amount of waste arriving at these disposal sites in the first place.

One of the most polluting wastes is plastic, specifically polyethylene terephthalate (PET), since its useful life is very short and it can take up to 100 years to degrade. One of the problems with this material is that it occupies a large volume of space and causes clogging of drains, seas and rivers, as well as invading the physical environment if it is not disposed of responsibly.

Another type of waste that is used in the production of the latticework is that generated by the construction industry, better known as "rubble" or special handling waste, as this sector is responsible for producing 45% of waste worldwide (Institute of Construction Technology (ITeC) 2022, para. 7).

For this reason, this article will show the design process that was carried out in order to create a lattice made from recycled materials and with the correct use of its properties to contribute to the energy consumption of a single-family house.

In order to design the lattice it was necessary to know more about the material used, so we will see background information about what polymer concrete is and how the recycled raw material was used to make it, we will see the recovery processes of each of its components, the beginning of the lattice design according to the NMX-C-441-ONNCCE-2013 standard and the moulds that were made to work with the recycled polymer concrete and obtain the final piece. Subsequently, in order to evaluate the lattice, mechanical, thermal, water absorption and fluid simulation tests were carried out. However, only the mechanical tests carried out on the lattice will be shown in this article.

1. Background of polymer concrete

Polymer concrete is a material composed of two phases, the first one is a polymeric matrix and the second one is a granulated reinforcement that can be natural stones such as sands, gravels, clays, marble, etc.

This material has good mechanical, physical and thermal properties, however, most of its applications today are made from polyester resins and natural aggregates, so the option of working from recycled aggregates was seen. When visiting the Materials Research Institute (IIM) of the National Autonomous University of Mexico (UNAM), Dr. Antonio Sánchez Solís gave the option of working with a polyester resin obtained from the chemical recycling of a PET bottle recovered from the rubbish. So we worked with this recycled unsaturated polyester resin as the polymeric matrix of the composite material and the granulated reinforcement was composed from recycled plain concrete, obtained from ACCUBO S.A. de C.V. located in Iztapalapa, Mexico City.

1.1 Unsaturated polyester PET resin

PET bottles are most frequently recovered in Mexico through mechanical recycling, however, when PET is subjected to this process it undergoes thermal and mechanical degradation, so that its properties will be modified to the original ones and even below those of virgin PET, so that it will require other processes or additives to improve its properties and comply with strict sanitary requirements demanded by the food industry.

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On the other hand, chemical recycling is an alternative and from this process the unsaturated polyester resin of PET is obtained, a glycolysis development is carried out and this is similar to the vulcanisation process used when manufacturing tyres, in this process some additives are added that will modify the polymer, whose objective is to create cross-links or bridges between the different chains of the original polymer. (Tecnología de los Plásticos, 2012, para. 1).

PET has a long spaghetti-like structure, formed by the bonds of many monomers, when it undergoes a process of glycolysis, the structure will separate into small parts and through the cross-linking of its bonds a polyester resin is obtained from this material.

This process is irreversible, since we are talking about a thermosetting resin and once it acquires its rigidity, it cannot be melted again, unlike thermoplastics that can be melted and rigidified as many times as required.

However, thermosets have other advantages, among them a high resistance to high temperatures, so that when they reach a higher temperature they begin to decompose, i.e. carbonise.

It is an alternative to recover a material through the decomposition of its parts and modify it to create another purpose.

Figure 1 shows how the resin with which we worked has a dark appearance that even looks dirty, but this is the result of the chemical process it was subjected to.

1.2 Recycled concrete

Simple concrete was used for the granulated reinforcement, in accordance with the classifications of construction and demolition waste presented in the NACDMX-007-RNAT-2019 standard.

The recovery process starts with the identification and separation of the type of material on site as a first step to facilitate its recycling

Figure 1 Unsaturated polyester resin from recycled PET
Source. Own photograph 2022

Standard 007 contains separation classifications, of which "concrete from prefabricated elements, concrete from structural and non-structural elements, concrete leftovers (without metallic elements)" was identified within category A) as simple concrete (Secretaria del Medio Ambiente [SEMANART], 2021. p. 100).

It is worth mentioning that when working with recycled aggregates it was detected that there is a non-uniform mixture of its components, i.e. traces of glass and red mud were found. The following figure shows the aggregates in their dry state.

Figure 2 Recycled granular aggregates
Source. Own photograph 2022

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2. Latticework design proposal

A lattice was designed, which is a masonry element of non-structural use for interior and exterior dividing walls, the latter being the most recommended.

For the design of the geometry, the first idea was to work with triangular shapes that would give greater stability to the wall, as if working with a reinforced structure, however, the complementary technical standards were consulted and "geometric and reinforcement requirements are imposed that are mainly based on the experience of the behaviour of real structures" (Official Gazette of Mexico City, 2020, p. 14).

Thus, when analysing the requirements of measurements, modulations and geometries, the original idea was changed without losing the essence of the design, so that the triangular shape was adapted to a prismatic one, as shown in figure 3. This was done in order to facilitate the transfer and placement of the piece so that it would not suffer any mishap such as spalling when it was handled on site.

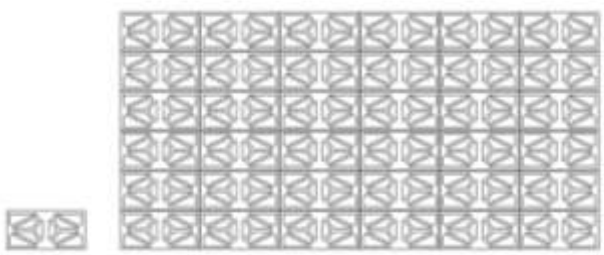

Figure 3 Second lattice proposal
Source. Own elaboration in AutoCAD 2022

Several empirical experiments were made with different moulds to see if the proposal worked with normal concrete casting, however, several observations were made after failed attempts, where the geometry was not adequate, since the thicknesses of the interior walls were 15 mm and as they were so thin the concrete did not enter easily, so the NMX-C-441-ONNCCE-2013 standard was consulted, which establishes the characteristics that partition walls, blocks, bricks and masonry elements must comply with. It was found that the minimum thickness in interior walls is 17 mm to work with concrete.

It was then decided to work with a square module that would allow to have the appropriate thicknesses and to join two pieces together to form the pattern of the original idea. As shown in the following figure.

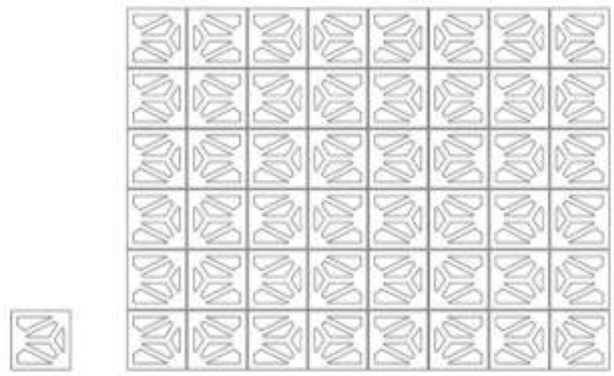

Figure 4 Final lattice proposal
Source. Own elaboration in AutoCAD 2022

2.1. Latticework dimensions

The lattice measures 19 x 19 x 10 cm (height, width, thickness) and complies with the net area of 50% of the gross area of the part. As shown below.

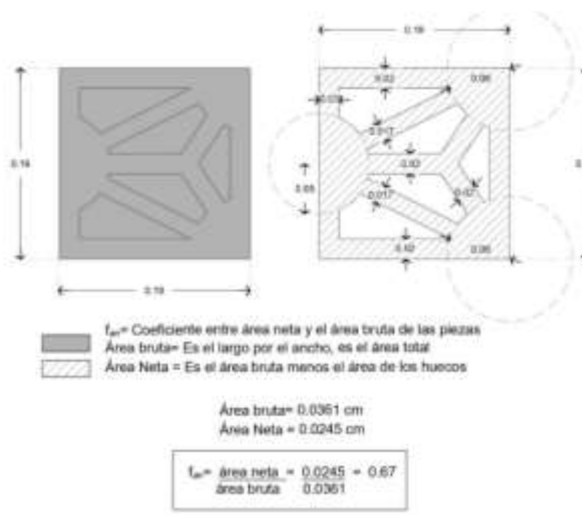

Figure 5 Net area of the lattice design
Source. Own elaboration in AutoCAD 2022

3. Preparation of moulds for its manufacture

To start working with the recycled polymer concrete, two moulds were required, a positive mould or mother mould, which was the main mould we worked with, and a negative mould to be able to make the positive mould.

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3.1. Negative mould

First the negative mould was made, where the lattice was modelled in Solidworks and printed at 1:1 scale in 3D with PLA filament, then the printed piece was placed in a wooden box to be able to make the silicone casting with which the final mould would be made. The result is shown in the following figure.

Figure 6. Negative mould made
Source. Own elaboration, Dalia Cruz Martínez 2022

3.2. Positive mould

The positive mould was made of P-53 silicone, which among the rubbers has good properties such as high resistance to tearing and is elastic, making it ideal for working with natural stones such as marble, granite and concrete.

The process required a catalyst or TP, which is an initiator that helps the vulcanisation process, this process goes through three important stages, first from a liquid to a solid state, the second is that there is a gel point, meaning that it is already sticky and finally the curing or total vulcanisation, when the silicone is completely solid.

Once the silicone is poured into the mould, it is left to cure for 24 hours, obtaining the following results.

Figure 7 Final positive mould
Source: Own elaboration, Dalia Cruz Martínez 2022.

4. Process of making the lattice with recycled polymer concrete

Once the final mould was obtained, work began at the Materials Research Institute (IIM) of the UNAM with Dr. Antonio Sánchez Solís, who provided the recycled resin with which work began.

Two sizes of aggregates of ¼" and 3/8" of an inch were used, which were perfectly mixed in a dry state.

A process similar to vulcanisation was carried out, i.e. a chemical reaction where the resin begins to harden and goes from a liquid to a solid state, as well as being an irreversible process, so the resin will acquire its maximum resistance in approximately 24 hours.

To carry out this process, a catalyst, a monomer and an accelerator were required, all the aggregates are perfectly incorporated and once they are homogeneously mixed, they are poured into the mould and left to cure for 24 hours to proceed with the demoulding of the final piece. The following figure shows the result obtained.

Figure 8 Pouring of aggregates and final result
Source: Own elaboration, Dalia Cruz Martínez 2022

Results

When the piece was demoulded, two types of finishes were obtained, a smoother one, which is where the resin was more concentrated, and a rougher part, which is where the granular aggregates that were used stand out more. Obviously each one will have different properties, the first is that the smooth part is totally impermeable to water and the rough texture allows the flow of water very well, which makes it a permeable finish.

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June 2023 Vol.7 No.17 16-25

This was the result of the effect of gravity in the mould, as the resin, being liquid, was concentrated in the lower part of the mould and the granular aggregate was more exposed in the upper part, so we proceeded to work with these results.

Once the work at the Materials Research Institute was completed, the material and the design of the proposed lattice were evaluated. To do this, 10 more pieces had to be made, of which they were made at home with the appropriate protection and the necessary care. The following figure shows the results achieved in the experimental phase of the production of the pieces.

Figure 9 Lattices obtained in the experimental phase
Source: Own elaboration, Dalia Cruz Martínez 2022

Recycled polymer concrete was proposed in a lattice because it is a non-structural element and recycled aggregates can currently be used in noble and masonry uses. In addition, by working with this material, favourable mechanical and thermal properties were obtained to propose it in an exterior wall of a single-family house in Cuautla Morelos.

5. Tests carried out to evaluate the geometry and the material used

It was necessary to evaluate the mechanical behaviour of the lattice through individual and diagonal compression tests, its thermal behaviour by measuring its thermal transmission coefficient (k), water absorption, i.e. resistance to humidity and finally digital fluid simulations were carried out to see how the wind behaves through the proposed geometry.

In this article only the mechanical tests will be discussed.

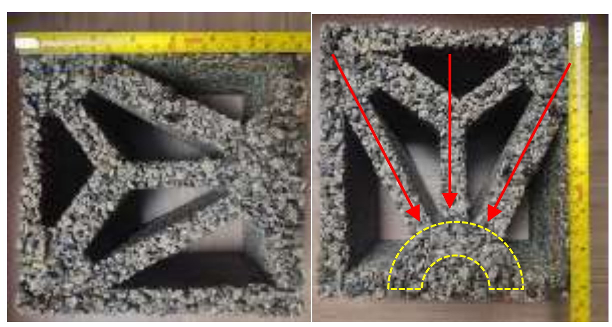
5.1. Mechanical tests

The individual compression test was carried out where a sample of at least 5 pieces was required. It is worth mentioning that 10 lattices were made at home with a custom workshop and I individually made as many pieces as possible.

The lattices, although they are not structural masonry elements, must have the necessary stability against external forces such as an earthquake or wind, so they must comply with the minimum resistances established by the NMX-C-036-ONNCCE-2013 standard that specifies the test methods for compressive strength tests of blocks, partitions, bricks, lattices and paving stones.

The tests were carried out on a universal machine in the mechanics of materials laboratory of Civil Engineering (L4) of FES Aragón, which has a capacity of 120 tonnes. Five pieces were individually subjected to this machine. The interesting thing about this test was that it was proved that the geometry of the lattice does influence the load capacity of the piece independently of the material used.

That is to say, 3 parts were placed horizontally, as shown in a) in the universal machine and supported half the load compared to when they were placed vertically, as shown in b) in figure 10. So when the lattice is placed vertically it has a capacity of 61.31 kg/cm2 this capacity is very good as it complies with the NMX-C-441-ONNCCE-2013 standard that establishes the minimum individual compressive strength for lattice pieces.



a) b)

Figure 10 Comparison of two ways of installing the lattice. Source. Own elaboration, Dalia Cruz Martínez 2022

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It is important to evaluate the individual resistance of the piece, however, its behaviour must be measured when it is already placed in a wall, to see how it works with the type of binder with which the lattice is going to be glued.

The second test was then carried out, where a 40 x 40 cm wall was made for the thickness of the piece and placed at home with the help of a master mason, then it was left to cure for approximately 8 days and the wall was taken to the Civil Engineering laboratory of FES Aragón to undergo the diagonal compressive strength test.

In this case, type I mortar was selected as the binder to glue the wall. This mortar has a compressive strength greater than or equal to 12.5 MPa (125 kg/cm2), so it was expected to have greater stability in the wall.

The wall was placed in the universal machine at 45 degrees with the appropriate heads to receive the load and not to displace the wall, as shown in figure 11.

The result was a shear failure, i.e. the bond between the masonry element and the binder failed. However, the diagonal compressive strength complies with the requirements of the NMX-C-464-ONNCCE-2010 standard for testing walls and piles, as it is within the parameters established in the standard.

The diagonal compressive strength was:

$$v'_{M} = \frac{Vm}{1+2.5Cv} = \frac{4.74}{1+2.5(0.1)} = \mathbf{3.792}$$

Figure 11 Laying of the wall in a universal machine. *Source. Own elaboration, Dalia Cruz Martínez 2022*

Conclusions

Technological advances in the development of materials are becoming increasingly progressive. Concern for the environment and the proposal to recover waste to be used in other applications in order to reduce the use of raw materials and reduce the pressure exerted on natural resources is an objective that is sought from the circular economy.

In the field of construction, it is the responsibility of the construction industry to take care of the waste that is generated on a daily basis.

It was demonstrated that elements for construction made from solid urban waste can be proposed and, through appropriate recycling, they can be used for a second application.

As lattices are part of a non-structural wall, this means that they do not form part of the load-bearing elements of the structure of a building, so their applications are dividing walls, parapets, parapets, facades, etc. However, these pieces need to be able to resist external actions to the structure, for example, their own weight, ground movements, such as an earthquake, and wind thrust if they are outside.

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As a result, the parts have to be analysed individually and placed in the final position in which they will work.

For the time being, favourable results were achieved in the individual compressive strength tests, as they comply with the NMX-C-441-ONNCCE-2013 standard on specifications for non-structural masonry pieces.

These tests were used to verify their individual resistance and the correct position in which they will be placed in the wall, as it was observed that, by positioning the lattice with the interior walls vertically, they would withstand twice the weight if they were placed horizontally.

On the other hand, in the diagonal resistance test, there was a shear failure, i.e. the adhesion between the resin or the smooth part of the lattice and the mortar failed, since the rough part had a better adhesion to the mortar. However, the parameters obtained are within the permitted limits of the NMX-C-464-ONNCCE-2010 standard, so the construction system with type I mortar is maintained.

However, improvements can be made to the design of the piece so that the smooth part can have a better adherence to the mortar, such as adding teeth or channels at the ends of the lattice so that it can receive the mortar and the diagonal reinforcement such as a rod, in order to finally have a better grip and avoid displacement.

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