Article

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Design of a methodology for the elaboration of ecological bricks incorporating low-density polyethylene

Diseño de una metodología para la elaboración de ladrillos ecológicos de concreto incorporando polietileno de baja densidad

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Abstract

Low-density polyethylene (LDPE) is generally found in the form of bags that are used to pack or transport merchandise; however, the proper disposal of this non-biodegradable material has been a great challenge, since, worldwide, it is calculated that only 9%, of the 9 billion tons that have been produced so far, has been recycled. In Mexico, it is estimated that 8 million tons of this material will be generated annually and only 14% will be recycled. On the other hand, the recycling of these residues, as an aggregate in construction materials, is considered an environmentally sustainable application. The objective of this article is to develop a methodology for the design of ecological concrete bricks incorporating LDPE from design as part of its aggregates, which will be obtained from articles with results presented, thus seeking to analyze the best design; this as an alternative to bricks commonly found in the construction industry. Although bricks made only with LDPE and sand have given good results, in relation to the use of plastic in intervals of 25 to 50%, it is expected that by adding Portland cement, they will have better physical and mechanical properties.

Plastic waste, Low density polyethylene aggregate, Design methodology, Constructive alternative

Resumen

El polietileno de baja densidad (LDPE), se encuentra generalmente en forma de bolsas que se utilizan para empacar o transportar mercancías; sin embargo, la disposición adecuada de este material no biodegradable ha sido un gran desafío, ya que, a nivel mundial, se calcula que solo el 9%, de los 9 mil millones de toneladas que se han producido hasta ahora, ha sido reciclado. En México, se estima que anualmente se generan 8 millones de toneladas de este material y solo se recicla el 14%. Por otra parte, el reciclaje de estos residuos, como agregado en materiales de construcción, se considera una aplicación ambientalmente sostenible. El objetivo de este artículo es desarrollar una metodología para el diseño de ladrillos ecológicos de concreto incorporando LDPE proveniente de desecho como parte de sus agregados, lo cual se obtendrá a partir de artículos con resultados presentados, buscando de esta manera analizar el mejor diseño; esto como una alternativa a los ladrillos que comúnmente se encuentran en la industria de la construcción. Si bien los ladrillos elaborados únicamente con LDPE y arena han dado buenos resultados, en relación al uso de plástico en intervalos de 25 a 50%, se espera que al agregar cemento Portland, estos tengan mejores propiedades físicas y mecánicas.

Residuos plásticos, Agregado de polietileno de baja densidad, Metodología de diseño, Alternativa constructiva

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Introduction

Pollution generated by plastic agents is a huge environmental problem for contemporary society (Charitou et al., 2021). The waste generated by residues, especially those that are considered single-use plastics, is a major challenge to be managed by the vast majority of countries worldwide (Taaffe et al., 2014). Plastic is a hazardous and polluting material, but at the same time, useful for the economic development of the global society (Kumar et al., 2020).

In the last 2 decades, the declining capacity of landfills to collect waste has resulted in the United States and the European Union introducing new legislation to promote waste reduction (Subramanian, 2000). Plastics have become a material that is part of our life, as many economic activities depend on the production of this material (Muthu et al., 2011); thus, the negative impact of plastic materials on ecology has been studied by several researchers (Shent et al., 1999; Mutha et al., 2006).

The annual global consumption of plastic materials has increased from about 5 million tonnes in the 1950s to almost 100 million tonnes in 2001 (Siddique et al., 2008). Table 1 shows the types and quantities of plastics generated in the United States, one of the world's largest waste generating countries (Siddique et al., 2008).

Plastic type	Quantity (1000 tons)
Polyethylene terephthalate (PET)	1700
High density polyethylene (HDPE)	4120
Low density polyethylene (LDPE)	5010
Polypropylene (PP)	2580
Polystyrene (PS)	1990
Others	3130

Table 1 Types and amounts of designer plastic generated in the United States in the 21st century
Source: (Siddique et al., 2008)

Globally, approximately 275 million tonnes of plastic waste were generated in 192 coastal countries in 2010, causing pollution in beach areas and damaging marine ecosystems, with 12.7 million tonnes of plastic waste entering the ocean (Ikechukwu & Shabangu, 2021).

There are plastic materials that, due to their versatility, are widely used; however, the proper management of their recycling is a long-standing problem (Grodzińska-Jurczak et al., 2022). Plastics such as LDPE are widely used for the manufacture of plastic bags (Martin et al., 2022), as the bags given to us in supermarkets, when shopping, are commonly made of LDPE because it is the most common way of transporting any goods (Gómez & Escobar, 2022).

LDPE is generally found in the form of bags used for packaging or transporting goods; however, the proper disposal of this non-biodegradable material has been a major challenge, as globally it is estimated that only 9% of the 9 billion tonnes that have been produced so far have been recycled (Senturk & Dumludag, 2020). In Mexico, it is estimated that 8 million tonnes of this material are generated annually and only 14% is recycled (Meert et al., 2021).

In recent decades, the use of plastic materials such as polyethylene terephthalate (PET) (Shent et al., 1999) and LDPE (Hampton et al., 1999) has increased, 1999) and LDPE (Hamzah & Alkhafaj, 2022), as part of the stone aggregates used in building elements used in the construction industry, has been a good alternative to contribute in a sustainable way to the development of new building materials, thereby supporting the environment, due to the growing concern for the use of building materials that are environmentally friendly, economical and lightweight; furthermore, building materials can benefit us by providing the material requirements without compromising nature (Kumar et al., 2020).

Several researches have been conducted to know the physical and mechanical characteristics of concrete building materials when mixed with some kind of plastic (Shent et al., 1999; Pancca, 2022); as well as on mortars containing PET as a substitute for fine aggregate (Hannawi et al., 2010); moreover, research has been conducted on the use of rice husk mixed with plastics as a concrete composite (Choi et al., 2006). Similarly, the properties of construction elements in which aggregates have been replaced by recycled plastics as part of the materials in concrete have been studied (Frigione, 2010; Akçaözoğlu et al., 2010; Ismail & AL-Hashmi, 2008; Ortiz, 2022).

Also, research has been conducted on the impact of water-cement ratios in concrete when mixed with PET bottles (Albano et al., 2009). There have even been articles on the characteristics of some plastics in combination with asphalt as reinforcement for different types of soil as a material for road layers (Babu & Chouksey, 2011). In addition, research has been carried out on the use of compressed earth bricks (Cabrera, 2022) and projects on the reuse of recycled materials, such as sawdust, in adobe walls (Ochoa, 2022) and other elements, used as methods of self-construction (Aceto & Benítez, 2022).

The use of plastic materials as aggregate in concrete and other construction elements is an ecological and sustainable option to the problem of pollution generated by them; however, it is important to mention that, according to the state of the art consulted so far, there is not much information regarding the use of LDPE in the form of waste plastic bags as a composite for concrete bricks, as the plastic has only been incorporated in combination with sand (Kumar et al., 2020).

LDPE is a commercial polymer widely used in a variety of applications. Due to the complexity of its molecular structure, which includes molecular weight distribution and randomly distributed long-chain branching, its rheological behaviour is varied (Dietrich et al., 2021).

The performance of sand and recycled LDPE composites has been analysed for their strength and durability. Mechanical properties such as compression, tension, water absorption, thermal conductivity, and thermal expansion have been tested and analysed in laboratory settings. In the study conducted by (Mohan et al., 2020), river sand was mixed with LDPE plastic in a 1:1 ratio. The test results showed that there is an acceptable performance of LDPE composite samples compared to conventional bricks. These results justify the suitability of using the developed composite as an alternative for construction applications.

Likewise, in the research conducted by Hamzah & Alkhafaj (2022), using remnants of medical syringes made of LDPE with the addition of river sand and sawdust in different proportions, it was shown that bricks made of plastic mixed with sawdust gave a good compressive strength of 6. 60 Mega Pascals (MPa), this when using 20% sawdust with 80% sand; this value was higher than that of the bricks made of plastic and sand, which obtained a value of 6.10 MPa using 60% sand with 40% LDPE. In both cases, the bricks gave a compressive strength similar to that of conventional bricks, as well as a very low absorption rate. Also, the density was very low, especially for the bricks containing sawdust, where the highest value was 0.89 grams over cubic centimetres (gr/cm^3) which represents almost only the density value of the pure polymer; and for the bricks containing sand and LDPE, the density value was 1. 43 (gr/cm^3); furthermore, good hardness values were obtained in laboratory tests for both types of bricks. In this study, it was found that, when incorporating LDPE with sand, there is no chemical reaction, but only a physical reaction between the particles of both materials.

In addition, in 2016, the decrease in compressive strength was studied with the increase in the proportion of plastic from LDPE waste, and the effect of different plastic proportions, in different laboratory tests such as: compression test and water absorption test. It was concluded that the various proportions of 5, 15, 25 and 35 % of plastic waste, in combination with sand, had a maximum compressive load of 9.86, 10.46, 11.00 and 10.63 Newton over square millimetre (N/mm^2) respectively. Through this study, it could be seen that the bond between plastic particles and sand is weak after a certain limit; however, the mixtures of sand bricks and plastic waste resulted in almost zero water absorption (Gopu et al., 2016).

Also, in 2020, the use of recycled plastic in ecological bricks was studied, and it was concluded that they have a compressive strength similar to that of cement and sand bricks, since the compressive strength of ecological bricks was 2700 kilograms over square centimeters (kg/cm^2) and the moisture content was 0.74 %. The bricks, although of good quality, do not absorb more than 5% water; moreover, the mixture of sand and plastic gives optimum results as in a conventional brick. The sample preparation of the bricks was generated by heating sand and plastic waste combined at 200 °C, and the ratio of plastic to sand was 1:1.5 (Kumar et al., 2020).

Ordinarily, the reuse of plastic waste as a building material has been studied by using plastic extrusion, and it has been observed that the maximum compressive load of plastic bricks is 13. 69 N/mm^2; furthermore, by adding other recycled material such as fly ash, strength values ranging from 10.42 to 11.48 N/mm^2 have been obtained; which is similar to that of conventional bricks (Anand et al., 2017).

However, research by Chauhan et al. (2019) showed that by mixing sand and LDPE plastic in different ratios such as: 1:2, 1:3 and 1:4, the optimum amount of plastic that could be used to achieve acceptable compressive strength, i.e., 203. 56 kg/〖cm〗^2, is the ratio 1:2. By using these amounts, the water absorption varies from 0.94 to 1.22% which is a good result compared to bricks normally used in the construction industry.

However, the use of LDPE plastic has not only been investigated in construction elements such as bricks or partition walls; it has also been used in combination with asphalt as an aggregate for some asphalt mixes (Ullah et al., 2021; Singh et al., 2022; Abduljabbar et al, 2022; Genet et al., 2021), according to the literature, adding polymers to asphalt binders helps to improve the bond between the aggregate and the binder, which can help to improve numerous characteristics of asphalt pavements (Singh et al., 2022).

On the other hand, LDPE polyethylene plastic waste can act as substitutes for natural aggregates in asphalt; furthermore, synthetic plastic aggregates have resulted in the reduction of asphalt; in the study conducted by (Ullah et al., 2021), it was shown that by replacing natural aggregates with LDPE in proportions such as 5, 15 and 25%, the density of the asphalt mixture is reduced due to the increase of air voids, in addition, the stability and flowability values increase by up to 15%; it is important to mention that the dynamic modulus of asphalt also improved with the incorporation of LDPE in the asphalt mixture.

Subsequently, in the research carried out by Singh et al. (2022), LDPE was partially replaced by stone aggregates in bituminous mixes, using an organic additive; furthermore, thanks to laboratory tests, it was possible to prove that, when using four different percentages of bitumen content (4. 2, 4.7, 5.2 and 5.7 %), in contrast to a constant percentage of 3% by weight of bitumen, with varying percentages of LDPE, such as 2, 4 and 6% respectively, the stability of the asphalt mixes is increased; thus, in this research the maximum stability was achieved with 4% plastic and 3% additive.

In this way, it has been proven that waste LDPE plastic bags can improve the performance of the thin asphalt layer, in addition to improving the stability of the asphalt binder, as in the research carried out by Abduljabbar et al. (2022), in which three doses of LDPE were incorporated with asphalt binder in proportions of 2, 4 and 6%, when performing typical laboratory tests for asphalts, such as: Marshall stability and flow, indirect tensile strength, creep compliance, skid resistance, wheel track, abrasion loss and tensile strength ratio, substantial improvements were obtained in the performance of LDPE modified asphalt compared to the control mix. Importantly, for this study, the preeminent improvement was obtained in the creep compliance test, where the creep compliance value decreased by 83% compared to the control mix when 6% LDPE was used. This study concluded that the use of waste material is an effective method of asphalt modification that also contributes to promoting environmental sustainability.

However, the use of LDPE from waste has had different applications in different areas of the construction industry, showing its effectiveness in the incorporation as a partial substitute material for the aggregates of different construction elements. Taking as a reference the fact that waste plastic in the form of LDPE is a viable option for use in combination with other materials, a methodology will be developed to study its use as a complementary material in concrete bricks, since the use of waste plastics as construction materials, especially in the manufacture of blocks and bricks, is one of the best techniques to achieve sustainable waste management.

Table 2 shows different types of plastic, their physical properties, as well as the use that can be given to them when combined with stone aggregates, as a complementary material in construction elements used in the construction industry, in this case, it can be noted that the use of LDPE in the manufacture of bricks is feasible (Shailendra, Singh, Chauhan et al., 2021).

No.	Plastic composition	Physical properties	Possible construction uses
1	PC	Hard and stiff	Total in cement mixture
2	PP	Flexible and hard	Total in asphalt mixture
3	LDPE	Flexible	Bricks and Blocks
4	PS	Brittle and hard	insulation material
5	HDPE	Rigid	Plastic Wood, Tables and Chairs
6	PET	Flexible and hard	Filaments in cementitious pieces

Table 2 Plastic composition, its physical properties and its possible constructive uses
Source: (Shailendra Singh Chauhan et al., 2021)

According to the literature consulted, LDPE has been used efficiently in the production of bricks; moreover, its versatility has been seen when incorporated with sand (Hamzah & Alkhafaj, 2022; Mohan et al., 2020; Gopu et al., 2016; Murts et al., 2021; Abid et al, 2021); however, most of the previously employed methodologies only use sand in combination with LDPE; therefore, it is expected that by incorporating a material that is commonly used in bricks used in the construction industry, i.e., Portland cement, better physical and mechanical capabilities will be obtained, thereby achieving greater constructive applications.

The objective of this article is to develop a methodology for the design of ecological concrete bricks incorporating LDPE from waste as part of its aggregates, which will be obtained from articles with results presented, thus seeking to optimise the best design; this as an alternative to the bricks normally found in the construction industry.

Theoretical background

The origin of polyethylene was in 1898, when Von Pechmann obtained a polymer with a structure equivalent to polyethylene, calling it polymethylene. This synthesis was produced almost accidentally from diazomethane, resulting in a polymer with a low molecular weight. In 1900, Bamberger and Tschirner analysed a similar product. LDPE was similarly obtained by Michaels' high-pressure ethylene studies in Amsterdam. This discovery was exploited by Gibson to produce polyethylene from a mixture of ethylene and benzaldehyde. In 1935, in England, chemists and engineers W. Faucett, G. Paton, W. Perrin and G. Williams, polymerised ethylene using high pressures and temperatures (Levett al., 1970).

Polyethylene is defined as a thermoplastic synthetic polymer. It is a partially crystalline and partially amorphous material, whitish in colour and translucent. The various types of polyethylene found on the market are the result of different operating conditions, carried out in the polymerisation reaction (Molina Flores et al., 2020).

The chemical structure of polyethylene is $-(CH_2-CH_2-)n$. This molecule is composed in its structural unit by two carbon atoms and 4 hydrogen atoms all linked by covalent bonds. The strength of the C-C and C-H bonds is 347 and 414 kilojoules per mole (Kj/mol) respectively. This basic unit can be repeated indefinitely to form polyethylene. The number of times this basic unit is repeated depends on the type of catalyst used in the chemical reaction, temperature and pressure (Amelia et al., 2021).

A polyethylene molecule is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom (Figure 1) (Coreño & Méndez, 2010).

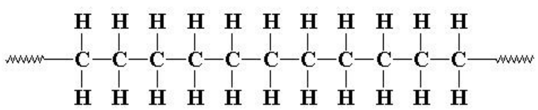

Figure 1 Atomic composition of polyethylene
Source: (Coreño & Méndez, 2010).

Sometimes some of the carbons, instead of having hydrogens attached to them, have long polyethylene chains associated with them. This is called branched polyethylene, or low density polyethylene, or LDPE (Figure 2) (Santagata et al., 2020).

Figure 2 Branched polyethylene molecule or LDPE
Source: (Santagata et al., 2020).

Objects made of LDPE are identified in the American SPI (Society of the Plastics Industry) identification system with the symbol on the bottom or back (Figure 3) (Vaid et al., 2020).

Figure 3 LDPE identification symbol
Source: (Vaid et al., 2020)

A) The LDPE production process

Depending on the type of polyethylene to be produced, both the polymerisation mechanism and the system used to carry out the reaction may vary.

a. Free radical polymerisation

This process produces LDPE. This reaction takes place at high pressures (1000-3000 bar) and temperatures between 100 and 300 °C, with short polymerisation times (15 seconds to 2 minutes) and in tubular reactors or autoclaves. Small amounts of oxygen or hydrogen peroxide can be used as initiating compounds. The polyethylene thus obtained has numerous branches with short and long chains, due to the side reactions that occur under the conditions used (Das & Kumar, 2021).

b. General characteristics of LDPE

LDPE can be found in different presentations, but the most common ones are: medical syringes, plastic bags and sacks, cups, pipes, toys, cables, plastic containers and caps, milk cartons (as one of the insulating layers), containers for detergents and other chemicals, car parts, etc. (Hariadi et al., 2021). Generally speaking, this material has a density of 0.910-0.940 gr/ 〖cm〗 ^3 with a high degree of branching of both long and short chains, which means that the chains do not compact properly to form a crystalline structure. Its melting temperature is 110 °C. Its tensile strength is low and its ductility high, which makes it easy to process (Coreño & Méndez, 2010).

B) Physical, Mechanical and Thermal Properties of LDPE

Below is a series of tables containing information regarding the most important properties of LDPE. It is necessary to consider the values of these characteristics, as they may have an influence on the concrete mixed with LDPE, when subjecting the eco-bricks to laboratory tests as part of the experimentation necessary to know their physical, mechanical or thermal properties.

Mechanical properties are perhaps some of the most important properties to consider for masonry or concrete bricks. Table 3 shows some of the mechanical properties of LDPE, characteristics that are necessary to consider, because of the possible influence they could have on green bricks.

Among these characteristics of LDPE are tensile strength, tensile modulus and impact resistance, which are interesting to consider because of the impact that could be made by incorporating LDPE into a brick (Das & Kumar, 2021).

Property	Measure
Elongation at Break (%)	400.00
Traction Module (Gpa)	0.10 – 0.30
Tensile strength (Mpa)	5.00 – 25.00
Impact resistence (J/m^2)	> 1000.00

Table 3 Mechanical properties of LDPE
Source: (Majeed et al., 2018)

Table 4 shows the most important thermal properties of LDPE, these properties are interesting to consider, since mixing LDPE plastic with concrete is likely to expose the green bricks to elevated temperatures. Some necessary properties to consider are, for example, specific heat and thermal conductivity (Datta et al., 2019).

Property	Measure
Specific heat ($J/Kg * K$)	1900.00
Coefficient of thermal expansion ($x10^{-6}/K$)	100.00 – 200.00
Thermal Conductivity at 23°C ($W/m * K$)	0.33
Maximum temperature of use (°C)	50.00 – 90.00
Minimum temperature of use (°C)	- 60.00

Table 4 Thermal properties of LDPE *(Datta et al., 2019).*

Table 5 shows the most important physical properties of LDPE, including absorption and density, which are interesting to consider, as they are characteristics that are evaluated in the laboratory to know the virtues of masonry units, such as bricks. Therefore, it is important to know the values that LDPE has and thus evaluate, in a future design, the impact they will have on the bricks. Another important property is flammability, since being a plastic material and when combined with any aggregate, LDPE's own characteristics can evoke some kind of reaction (Awad & Abdellatif, 2019).

Property	Measure
Water Absorption - in 24 hours (%)	< 0.02
Density (gr/cm^3)	0.92
Refractive Index	1.51
Limit Oxygen Index (%)	17.00
Inflammability	Yes
Ultra-violet resistance	Acceptable

Table 5 Physical properties of LDPE *(Awad & Abdellatif, 2019).*

A. Cement and Portland Cement

Cement is a ground hydraulic conglomerate which, when combined with water, forms a paste that sets and hardens through reactions and hydration processes. Portland cement is obtained by calcining a mixture of limestone and clay or other materials of similar overall composition at temperatures between 1300-1500 ºC, which causes a partial melting of these materials. The product obtained after calcination is called clinker, which, once ground with a small amount of gypsum, is called cement (Organismo Nacional de Normalización y Certificación de la Construcción y Edificación, 2001).

B. Sand

Stone aggregates are natural materials subject to disintegration, screening, crushing or washing treatments that are mixed with portland cement and water to form hydraulic concrete. Fine aggregate is natural sand obtained by crushing and screening, with particle sizes between seventy-five micrometres (5 μm) and four point seventy-five millimetres (4.75 mm) (Secretaría de Comunicaciones y Transportes, 2019).

C. Masonry

Masonry is defined as a set of pieces joined together, using a material such as mud or cement mortar; the units can be natural (stones) or artificial. The most commonly used masonry in the construction industry is composed of bricks made from concrete, mortar or annealed clay, because for years they have proven to be the best choice for use in walls and partitions (Moayedian & Hejazi, 2021).

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Methodology

Based on the scientific method and with the help of the literature review consulted, the most ideal methodology for the elaboration of ecological bricks will be evaluated, as well as the most optimal proportions of materials, following in an orderly manner the following activities. It is important to mention that most of the procedures will be based on international articles that contain the best and most representative results obtained, since, at the time of this research, not much information was found in similar investigations carried out in Mexico.

A. Activity 1. Define the most important specifications for bricks according to the Mexican standard for masonry (NMX-C-404-ONNCCE-2012).

In order to know the most important parameters to be considered when evaluating the properties of masonry, in this case bricks, the specifications contained in the Mexican standard for masonry NMX-C-404-ONNCCE-2012 (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012) will be used.

B. Activity 2. Collection of LDPE from Waste

In order to know the most viable ways and places to collect LDPE from waste, previous reported studies will be used as a reference.

C. Activity 3. How to Shred Waste LDPE

Once there is a sufficient quantity of LDPE material in the form of plastic bags, it will be shredded, crushed or reduced, as appropriate, to the particle sizes reported by the various authors consulted in the literature.

A. Activity 4. Obtaining the stone aggregate (sand) and cement for the concrete mix.

The materials (sand and cement) will be collected in a house or materials bank in the Municipality of Querétaro in the State of Querétaro, Mexico. The geological origin will be chosen according to previous research reports.

B. Activity 5. Specify the characteristics (granulometry, density, etc.) of the stone aggregate to be used for the production of ecological bricks.

With the help of the bibliography consulted, the most important characteristics of the sand will be defined, which will be considered for the elaboration of the ecological brick.

C. Activity 6. Specify the type of Portland cement to be used for the production of the ecological brick.

With the help of the consulted bibliography, define if Portland cement has been used and if so, define the type and characteristics of the cement to be used for the production of the ecological brick. If this material has not been used in previous studies, a percentage of incorporation will be proposed.

D. Activity 7. Specify the optimum percentages of LDPE in the ecological brick specimens.

With the help of the bibliography consulted, the most suitable percentages of LDPE in combination with sand and cement will be defined to give the best results for the different ecological concrete brick specimens.

E. Activity 8. Specify the Type of Mixing Between LDPE and Cementitious Material

Based on the literature review, determine how to incorporate LDPE into the concrete mix for the production of bricks, analyse whether the existing ways are environmentally sustainable, and if not, propose a different way.

F. Activity 9. Define the Most Important Laboratory Tests for Experimentation on Concrete Bricks

Based on the bibliography and the Mexican technical standards for masonry, define the laboratory tests necessary to be able to make decisions on the possible future construction applications of the ecological bricks.

G. Activity 10. Analyse Data on Physical-Mechanical Properties of Ecological Bricks using LDPE

Considering the results of laboratory tests, proportions and dimensions used in LDPE ecological bricks reported by the consulted bibliography, a comparative analysis of data versus what is specified in the Mexican standard will be carried out.

H. Activity 11. Report of Results

A report will be made, in which the most efficient way found to produce ecological concrete bricks incorporating LDPE as part of its aggregates will be presented.

I. Flowchart of Activities to be carried out for the research work.

Based on the methodology described above, Figure 4 is shown, which presents in an orderly manner the flow chart with the order of activities to be carried out for this research.

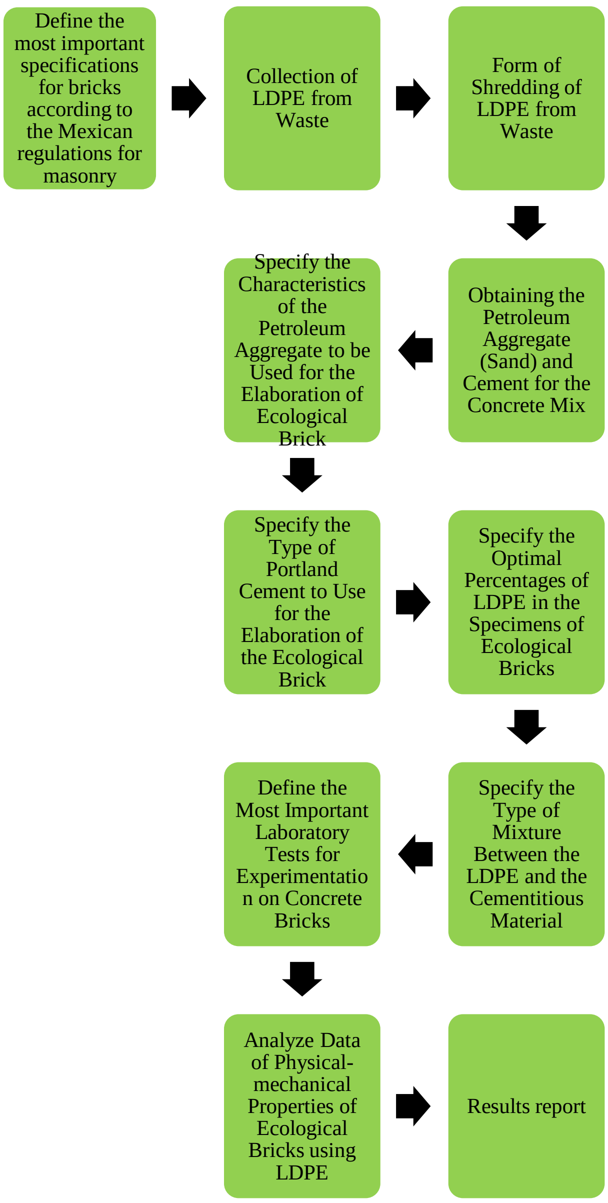

Figure 4 Flowchart with order of activities to be carried out for the research project

Results and discussion

A. Specifications for Masonry according to Mexican Standard NMX-C-404-ONNCCE-2012.

Below are some tables containing the most important recommendations and general specifications for masonry (blocks, partition walls or bricks and partitions) contained in the Mexican standard NMX-C-404-ONNCCE-2012 (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012). These parameters are interesting, as they give a reference range with respect to the different masonry elements, including the bricks studied in this paper.

a. Most common dimensions for masonry

Table 6 shows the recommended dimensions for different types of masonry (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012). It is considered that there may be a tolerance of ±3 mm in height, as well as ±2 in length and width, for each of the elements shown below.

Brick or masonry unit	Measures in millimeters (mm) Height	Length	Width (minimum)
Blocks	200	400	100
Clay bricks	50	190	100
Concrete bricks (tabicon)	60	240	100

Table 6 Dimensions for Masonry According to Mexican Standard NMX-C-404-ONNCCE-2012
Source: (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012)

As a recommendation, the Mexican standard for masonry NMX-C-404-ONNCCE-2012 (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012), establishes dimensions that should be used for the production of bricks. Based on these specifications, it will be possible to check whether previous methodologies for the production of ecological bricks have complied with these guidelines.

b. Compressive Strength for Masonry

Table 7 shows the compressive strength of masonry for structural use as specified by the NMX-C-404-ONNCCE-2012 standard (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012). It is important to consider these values, since the use of the bricks studied will depend on them, also, these values give the specific values to be used for masonry elements that are used in Mexico.

Masonry Unit	Medium resistance (Mpa)	Individual minimum resistance (Mpa)
Blocks	15 (150)	12 (120)
Clay bricks	11 (110)	7 (70)
Concrete bricks (tabicon)	11 (110)	7 (70)

Table 7 Compressive strength for masonry according to Mexican standard NMX-C-404-ONNCCE-2012
Source: (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012)

From the table above, it can be seen that the individual resistance ranges for masonry vary from 7 to 12 Mpa, these resistance values are the minimum that any type of masonry intended to be used as a construction element should comply with.

c Initial Water Absorption and Total Water Absorption in 24 hours for masonry

Table 8 shows the absorption values to be met by the different types of masonry commonly used in the construction industry, according to the Mexican standard NMX-C-404-ONNCCE-2012 (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012). All masonry elements are expected to present such values.

Masonry unit	Initial absorption for walls exposed to the outside (g/min)	Initial absorption for interior or coated walls (g/min)	Total absorption in 24 hours (%)
Concrete	5.00	7.50	12.00
Craft clay	Not specified	Not specified	23.00
Extruded or pressed clay	5.00	7.50	19.00

Table 8 Initial absorption and total water absorption values in 24 hours for masonry according to Mexican standard NMX-C-404-ONNCCE-2012
Source: (Organismo Nacional de Normalización de la Construcción Y La Edificación, 2012)

The table above shows the absorption values that masonry must meet, depending on the type of wall application in which it is intended to be used. The most important values are those representing the total absorption in 24 hours, which vary from 12 to 23 %.

B. Characteristics of Elaborated Ecological Bricks according to the State of the Art

A critical analysis of the results obtained by different researches will be carried out, in order to generate a methodology following already specified and researched parameters; trying to improve previous methodologies. The research presented only contemplates the results of those authors who obtained the best results according to the literature consulted.

a. Waste LDPE collection method

According to the literature, the method of collection of LDPE from waste has varied according to the different authors and the conditions specified in the objectives of their research work. Table 9 presents a summary of these methods, as well as the sites from which the waste LDPE has been obtained, since the purpose of all the investigations consulted has been to use only waste product.

Reference	Collection method	Waste form of LDPE
Hamzah & Alkhafaj (2022)	Plastic waste from a medical syringe factory	Medical syringes
Mohan et al. (2020)	Landfills for LDPE plastic waste from different sites	Various types of waste material
Gopu et al. (2016)	LDPE plastic waste from open dumps	Plastic bags
Chauhan et al. (2019)	LDPE plastic waste from open dumps	Various types of waste material

Table 9 Collection and shape of LDPE for the production of ecological bricks

According to the table above, it can be seen that LDPE from waste can be obtained from different materials, the important thing for the research to be carried out will be to choose a material that is widely used by society in general and that is also easy to collect, in this case, it is proposed to collect plastic bags, as it is a very abundant material in the form of waste, which can be found in different places such as: landfills or outdoors, markets, public roads, among others. This is due to the poor ecological awareness of contemporary society.

b. Method of shredding or shredding of waste LDPE

The method of incorporation between LDPE and complementary materials such as sand, has been diverse, this has been carried out according to the form and research objectives of each of the authors who have used this material in the production of ecological bricks. In each investigation, the most viable method of incorporation is used and with which it is hoped to obtain the best results. Table 10 shows the way of working or crushing LDPE followed by the most representative authors.

Reference	Crushing way
Hamzah & Alkhafaj (2022)	Melted directly with fire in a closed tank
Mohan et al. (2020)	Reduction to granules of less than 5 mm and after that, melted on fire
Gopu et al. (2016)	Melted directly with fire
Chauhan et al. (2019)	Reduction to granules by grinding the material

Table 10 Form of crushing of LDPE for incorporation in ecological bricks.

From the table above it can be seen that, for the most part, LDPE has been melted with fire and then incorporated with sand. In this case, most authors have only used sand and LDPE, the latter as a cementitious material. It is expected that by adding cement as an extra element to those already used, the ecological bricks will have more construction applications. For this reason, the incorporation of Portland cement will be studied in addition to the materials already incorporated in the production of bricks by the literature consulted.

c. Method of obtaining the stone aggregate (sand) and cement for the concrete mix or cementitious material.

Most of the ecological bricks that have been investigated have been made with some type of stone aggregate, most of which, obviously, has been sand. The sourcing of this aggregate as part of the brick making materials can vary depending on what the objectives of each type of brick are. Table 11 shows some of the sites from which stone aggregates, in this case specifically sand, and if applicable, cement, have been sourced for the production of ecological bricks. It is important to mention that those bricks that do not use cement have used LDPE as a cementitious material, which helped to physically bind the materials used.

Reference	Site of origin of stone aggregate (sand)	Site of origin of stone aggregate (cement)
Hamzah & Alkhafaj (2022)	River sand obtained from the nearest material bank	Not used
Mohan et al. (2020)	River sand originating from the southern states of India, Kerala and Tamil Nadu	Not used
	Manufactured sand obtained from recycling	
Gopu et al. (2016)	Manufactured sand obtained from recycling	Not used
Chauhan et al. (2019)	River sand obtained from the nearest material bank	Not used

Table 11 Site of origin of stone aggregates used in the elaboration of ecological bricks

It can be seen that all the research reviewed only makes use of sand and LDPE. It can also be noted that, as part of the collection of waste generated by the construction industry, and as an ecological contribution, use has been made of manufactured sand (recycled sand); however, in the same way, use has been made of a very common type of sand, such as river sand, which is more viable to use given its ease of use and availability, as it is a common stone material.

a. Characteristics of the fine aggregate used in the production of ecological bricks

Sand is a common and essential aggregate in the production of bricks, whether they are ecological or common, therefore, the influence it can have on the physical or mechanical properties of the bricks can be important, due to the characteristics of the fine material itself. Table 12 shows the physical properties of the sand used by different authors in the production of ecological bricks.

Reference	Granulometry	Density (gr/cm^3)
Hamzah & Alkhafaj (2022)	≤ 600.00 µm	1.38
Mohan et al. (2020)	≤ 2.36 mm	Not specified
	Not specified	Not specified
Gopu et al. (2016)	Not specified	Not specified
Chauhan et al. (2019)	≤ 600.00 µm	Not specified

Table 12 Characteristics of fine aggregate

When analysing the above data, it can be seen that the characteristics studied such as granulometry, geological origin and density of the sand is varied or even not mentioned; however, when analysing the results of the laboratory tests, it will be analysed with which physical properties of the sand the results obtained can be the best compared to what is dictated by the Mexican standards for masonry.

b. Portland cement type

It was mentioned above that no methodology consulted so far has used Portland cement as an aggregate for ecological bricks. Therefore, and as an objective of this article, a methodology will be designed that contemplates the incorporation of this material, thus giving greater versatility to bricks that have previously been developed using only LDPE plastic waste in combination with sand.

c. Percentages of LDPE in brick production

The reaction of environmentally friendly bricks by incorporating different percentages of LDPE in combination with sand has been investigated. Different authors carried out tests, substituting a percentage of the total materials used in LDPE ecological bricks, in order to find out to what extent the best results are obtained. Table 13 shows the quantities of this material used by different researchers; it can also be seen which is the percentage with which the best properties are reported in their laboratory analysis.

Reference	Incorporated percentages of LDPE (%)	Most optimal percentage of LDPE (%)
Hamzah & Alkhafaj (2022)	40, 50, 60, 70, 80 and 90	40
Mohan et al. (2020)	50	50
Gopu et al. (2016)	5, 15, 25 and 35	25
Chauhan et al. (2019)	20, 25 and 30	30

Table 13 Percentages of incorporation of LDPE in ecological bricks

According to the table above, it can be seen that the amounts of replacement or substitute of LDPE for sand, with which good results have been obtained, vary from 25 to 50 %. By incorporating a material such as cement, the amount of sand per cement will be reduced proportionally, maintaining the amounts of LDPE reported as acceptable, in order to know the reaction of the ecological bricks when incorporating a cementitious material such as Portland cement.

a. Mixing of Sand and LDPE

The ecological bricks that have been made by various authors in the past were the result of combining two materials: sand and LDPE, the latter as a waste material. In order to combine these aggregates, different processing procedures and tools were used. Table 14 shows the way in which these materials have been mixed and incorporated, as well as the most important tools used for this purpose; it also shows the dimensions of the moulds into which the mixture is poured, which later gives rise to the bricks.

Reference	Sand and LDPE incorporation method	Instruments or equipment used
Hamzah & Alkhafaj (2022)	- Plastic waste was melted in an oven and joined by hand with the help of an agitator in the sand	- Oven heated to 170-190 °C Mixing tray - -Steel mold for brick walls with dimensions 14.5x8.5x3 cm
Mohan et al. (2020)	- Mixing was carried out in a simple pot, heated from below by a flame, along with manual stirring with a paddle. - In addition to this, the plastic and sand were mixed together before being heated	- Steel pot Mixing device for fire - Steel mold with dimensions 15x29x2 cm
Gopu et al. (2016)	- LDPE plastic was mixed with sand with the help of a mixing machine, then both materials were melted in the melting machine	- Mixing device - Device for melting plastic material by means of fire - Mold for wooden bricks with dimensions of 6x12x24 cm
Chauhan et al. (2019)	- The mixture between sand and LDPE is heated with fire until the plastic melts and joins with the sand	- Mixing device - Device for melting plastic material by means of fire - Mold for steel bricks with dimensions of 23 x 10 x 7.5 cm

Table 14 Methods of incorporation of materials in the elaboration of bricks and used instruments

It can be noted that, in order to mix sand with LDPE, fire has been used to heat a container and melt the plastic. From the table above, it can also be seen that most of the bricks produced do not comply with the dimensions specified by the Mexican standard for masonry. It will be sought that the bricks to be produced in the future comply with these measurements; in addition, fire will not be used, as heating the plastic with it can generate toxic gases. It is important to mention that, by not using LDPE alone as a cementitious material and using Portland cement, it will no longer be necessary to use fire to adhere the materials.

a. Laboratory Tests

According to the Mexican standards for masonry, there are 2 fundamental laboratory tests to know the properties of any type of brick to be used in the construction industry. Several researches have used some tests to know certain parameters in the ecological bricks produced, Table 15 shows these tests.

Reference	Laboratory tests performed
Hamzah & Alkhafaj (2022)	1. Compressive strength 2. Water absorption (24 hours) 3. Density test 4. Hardness test
Mohan et al. (2020)	1. Resistance to compression 2. Split tensile strength 3. Water absorption (24 hours) 4. Thermal conductivity 5. Coefficient of thermal expansion
Gopu et al. (2016)	1. Compressive strength 2. Water absorption (24 hours) 3. Efflorescence test
Chauhan et al. (2019)	1. Compressive strength 2. Water absorption (24 hours) 3. Fire resistance test

Table 15 Number and type of laboratory test performed on ecological bricks.

Most of the research carried out has complied with the number and specifications of the standards that must be carried out on the masonry used as a construction element. In the experimentation carried out on concrete bricks mixed with LDPE, the aim is to at least comply with the number of tests recommended by the Mexican regulations for masonry, in order to find out whether these bricks can be used in construction elements that require their use. It is worth mentioning that all the references presented are those that present the best results obtained in previous methodologies and research, in addition, the results of these authors can be considered as the most representative for the development of this work.

A. Comparison between Results Obtained by Different Authors in the Elaboration of Ecological Bricks in Contrast with Mexican Standard Specifications for Masonry

a. General summary of reported results on ecological bricks

Table 16 below presents a summary of the most important data to be considered with respect to the Mexican standards for masonry. These data will be compared with the reference values of the 2 laboratory tests necessary to evaluate the characteristics of masonry elements, as well as the standard measurements that masonry must comply with to be used in a structural way in construction elements such as walls or similar.

Reference	Laboratory test evaluated by standard		Dimensions (mm)
	Total absorption in 24 hours (%)	Compression (Mpa)	
Hamzah & Alkhafaj (2022)	0.50	6.10	145x85x30
Mohan et al. (2020)	1.01	14.00	290x150x20
Gopu et al. (2016)	1.00	11.00	240x120x60
Chauhan et al. (2019)	1.23	19.96	230x100x75

Table 16 Parameters evaluated in ecological bricks necessary to comply with respect to masonry standards

b. Compliance of values with respect to Mexican Standards for Masonry

Table 17 is presented below, which will help to better understand whether the bricks produced by different authors comply with the standards of the 2 fundamental tests established by the Mexican masonry standards, as well as with the specified dimensions, since for an element to be used optimally in the industry, it must have certain characteristics that guarantee its good performance.

Reference	Does it comply with the values specified by the Mexican masonry regulations?		
	Total absorption in 24 hours (%)	Compression (Mpa)	Dimensions (cm)
Hamzah & Alkhafaj (2022)	No	No	No
Mohan et al. (2020)	No	Si	No
Gopu et al. (2016)	No	Si	No
Chauhan et al. (2019)	No	Si	No

Table 17 Compliance with values regarding Mexican regulations for masonry

Based on the table above, it can be seen that 3 of the 4 authors compared, which are the most representative, have complied with the reference value of the masonry compressive strength test; however, none of them have complied with the parameters of standard masonry measurements, as well as with the 24-hour water absorption.

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Conclusions

The characteristics of environmentally friendly bricks, mostly made from waste LDPE and sand, have been reviewed. In the following, a set of conclusions drawn from the general review of this study are presented. In addition, some recommendations are given regarding the future development of an eco-brick design that considers the use of Portland cement as an aggregate to the materials already used in reported eco-bricks.

- Waste LDPE is a material that, when incorporated as a cementitious material together with sand in the production of green bricks, has been shown to give acceptable results in laboratory tests necessary to characterise the masonry.

- According to the literature review, the percentages of LDPE incorporation that give acceptable results, when combined with sand, in the production of ecological bricks, are those in the range of 25 to 40%, this only by mixing the two materials mentioned.

- The common way used by various authors to achieve a cement effect of LDPE in combination with sand is to heat the plastic with fire in closed devices; however, it is known that the burning of plastic materials generates environmental pollution, for this reason, in the future, another method of combination between the materials used for the production of ecological bricks will be considered.

- The type of fine aggregate used by different authors for the production of ecological bricks ranges from recycled sand to the most common, river sand, but the use of both types is considered optimal, although river sand (virgin sand) gives better results as it is a non-recycled material.

- The LDPE used by different authors comes from different waste sources; however, it is considered more viable to use this material in the form of waste plastic bags, as it is a more abundant material in the environment and generates more pollution given its use as a method of packaging and packing of everyday consumer products. In addition, by using a waste material, we are making a sustainable contribution to the environment, as not using this type of single-use plastic would generate more pollution than already exists on the planet.

- Most of the methodologies used for the production of ecological bricks only mix sand and LDPE and do not use Portland cement; however, it is expected that by incorporating this material as it is done in conventional bricks, the masonry or ecological bricks can have better physical and mechanical properties.

- The bricks elaborated from the reviewed methodologies do not contemplate the dimensions specified by the Mexican standards for masonry, therefore, it is necessary to use measurements of real bricks, in order to obtain more reliable and realistic results when using these elements in the construction industry.

- The use of portland cement in various construction elements has been shown to result in improved physical and mechanical properties. It has been observed that the reported ecological bricks do not make use of this material, and as a consequence, some parameters evaluated in masonry, such as absorption, have been reduced. Therefore, the use of cement is considered necessary to achieve better properties in ecological bricks.

- In order to develop an ecological brick design that considers the incorporation of Portland cement, the use of this aggregate in different proportions will be studied, partially replacing the fine aggregate (sand) and maintaining the percentages of LDPE reported as acceptable by the consulted literature.

- From an ecological point of view, the use of Portland cement is not entirely sustainable; however, the construction uses of this element are very broad, since its use provides better properties in construction elements, which is why its use is necessary. However, if its use is partially substituted in elements such as bricks, this undoubtedly contributes to the care of the environment and gives greater versatility, in this case, to bricks, which are in great demand in the construction industry.

- Some studies report that when combining sand with LDPE there is no chemical bonding but only physical bonding between the particles of both materials. For this reason, it is feasible to study what type of reaction will exist when Portland cement is added as a complementary material to those already used by previous authors in previously reported methodologies.

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