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Journal of Technological Engineering

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The works must be unpublished and refer to topics of sources innovation in electrical, engineering signal, amplification electrical, motor design science, materials in electrical power, plants management and distribution of electrical energies and other topics related to Engineering and Technology.

Presentation of Content

As first article we present, *SiO_2 nanoparticle/Polymer composite as anticorrosive coating for A-36 steel*, by MENDOZA-MIRANDA, Juan Manuel, CORTES-LÓPEZ, Alfredo, GONZÁLEZ-MÉNDEZ, Luis Fernando and GÓMEZ-RAMOS, Irma Beatriz, with secondment at the Instituto Politécnico Nacional, as the second article we present, *Design of a methodology for the elaboration of ecological bricks incorporating low-density polyethylene*, by MARTÍNEZ-ÁNGELES, Hugo, RÍOS-MORENO, José Gabriel, PÉREZ-REA, María de la Luz and TREJO-PEREA, Mario, with affiliation at the Universidad Autónoma de Querétaro, as the third article we present, *Implementation of a neural network of low computational cost for its application in arm prostheses*, by LEÓN-PERALTA, Jorge Luis, SÁNCHEZ-LARA, Rafael, VÁZQUEZ-ÁVILA, José Luis and YAÑEZ-VARGAS, Juan Israel, with affiliation at the Universidad Autónoma del Carmen and Universidad Politécnica de Juventino Rosas, as last article we present, *Numerical study of the influence of the micro pin fin arrangement on the thermal and hydraulic performance of a micro heat sink*, by ZUÑIGA-CERROBLANCO, José Luis, MONTECILLO-SILLERO, Saul Fernando, HORTELANO-CAPETILLO, Juan Gregorio and PÉREZ-GARCÍA, Vicente, with assignment at the Universidad Politécnica de Juventino Rosas and Universidad de Guanajuato.

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SiO_2 nanoparticle/Polymer composite as anticorrosive coating for A-36 steel

Nanopartículas de SiO_2/compuesto de polímero como revestimiento anticorrosivo para el acero A-36

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Abstract

Automotive paint is used on the surface of automobiles to decorate or beautify the vehicle. However, one of its main purposes is to prevent metal corrosion. Therefore, in this paper, the anticorrosive properties of an epoxy resin-based primer with silica nanoparticles (SPN) are investigated. The coatings were deposited on A-36 steel plates and their efficiency as anticorrosive coatings as well as their adhesion, hardness, finish, and durability properties were evaluated under accelerated aging tests simulating humid and hot weathering conditions.

Corrosion, Anticorrosive coatings, Silica nanoparticles, A-36 Steel, NPS/Polymer composite

Resumen

La pintura automotriz es aquella usada en la superficie de los automóviles, esto para decorar o embellecer el vehículo. Sin embargo, una de sus principales funciones es prevenir la corrosión del metal. En este trabajo se investigaron las propiedades anticorrosivas de un primer a base de resina epóxica con nano partículas de sílice (NPS). Los recubrimientos se depositaron en placas de acero A-36 y se evaluó su eficiencia como protectores anticorrosivos, así como propiedades tales como: adherencia, dureza, acabado y durabilidad ante pruebas de envejecimiento acelerado simulando condiciones de intemperie de humedad y calor.

Corrosión, Recubrimiento anticorrosivo, Nanopartículas de sílice, acero A-36, Polímero compuesto NPSs

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Introduction

Automotive paint is used on the surface of automobiles. It is usually thought that such paint is to decorate the vehicle to make it more attractive to the eye, however, that is not the main function since paint is to prevent corrosion or rusting of the metal (Grtzl T, 2019; Groysman A, 2010).

Corrosion is defined as the degradation of metals due to environmental factors such as humidity and acidic or alkaline conditions of the environment to which the metal is exposed. Corrosive agents are those that cause the metal in its basal state to lose electrons to increase its oxidation state, through the reaction shown in Eq. 1.

$$M \rightarrow M^{n+} + n\,e^- \quad (1)$$

Corrosion is a physicochemical phenomenon that causes the degradation of the metal due to the formation of a galvanic cell; as shown in Figure 1a. The metal oxidizes losing electrons and with agents of the medium such as oxygen form the metal oxide (see Figure 1b) that causes the loss of the material causing the decrease of its mechanical properties (Salazar-Hernandez, 2015).

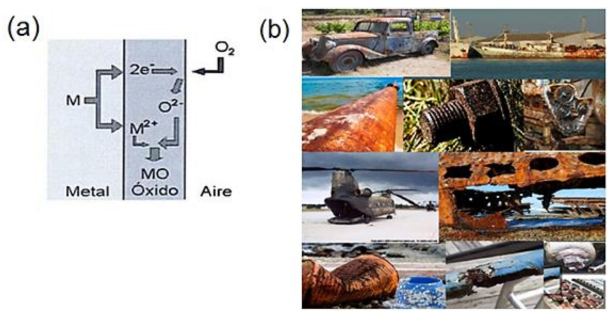

Figure 1 (a) Galvanic cell during corrosion (b) Example of materials with several corrosion

To prevent corrosion in metallic materials there are different alternatives, among them are anticorrosive coatings (Bierwagen G, 2010; Danaee I, 2014; Yi-Chia H, 2014; Wei T, 2005). Today, nanocomposites have been proposed; these are materials formed by the dispersion of inorganic particles with size or structure in the nanometer range in an organic phase, such as polymeric matrices (Zou H, 2008; Percy M.J, 2000; Yang F, 2006; Hung W.I, 2011). The inorganic particles give the material properties such as stiffness and thermal stability; while the polymeric matrix generally retains its flexibility, ductility and processability.

Among the inorganic phases that have been added to polymeric matrices for reinforcement are nanotubes, silicates (montrolite, saponite), metal nanoparticles (Ag, Au), metal oxides (TiO2, Al2O3, SiO2), semiconductors (PbS, CdS) (Zou H, 2008; Mahon J.R, 2022), grafted polymer with □-zirconium (Zhu Z, 2022). Being silicon dioxide (SiO2) one of the additives that have a greater importance due to the characteristics of silica (it is inert, with high thermal and mechanical stability), thus polymer/silica nanocomposites have a wide range of applications ranging from the formation of anticorrosive coatings (Honarvar Nazari M, 2016; Dave P, 2022), reinforcement in mechanical properties (LeBaron P.C, 1999), flame retardants (Kiliaris P, 2010) and biomaterials (Arcos D, 2010).

This paper presents the evaluation of the effect of the addition of silica nanoparticles to a commercial epoxy resin and determine the change in physical properties as well as its ability to act as a corrosion retardant on A-36 steel substrates.

Methodology

NPS/Polymer formulation

Table 1 shows the different formulation conditions performed for this research. The two main components in the formulations are epoxy resin (EP-2000) industrial grade catalyzed with ED-200 (industrial grade) and Aerosil-200 fumed silica (Aldrich, reagent grade). The amounts of silica nanoparticles in the polymer resin vary from 0.5 wt% to 10 wt.%. Two types of mixing were tested to obtain the coatings: magnetic stirring and ultrasound. On the other hand, formulations were obtained without solvent and adding acetone as solvent to improve particle dispersion in the resin.

The composites are applied on A-36 steel surfaces. Before applying the formulations, the metal surface is subjected to a pretreatment that consists of sanding the surface of the specimen with abrasive paper number 400 and washing with water and ethanol using an ultrasonic bath and finally drying the samples at a temperature of 50 ºC for 2 h.

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The coating is applied to the A-36 steel surface treated by immersion, which consists of introducing the metal sample into the solution containing the polymer/silica mixture and then leaving it to dry at a temperature of 50 ºC for 24 h, leaving the sheet in a vertical position.

	Epoxy Resin	NPS	Catalyst	Magnetic mixed	Ultrasound mixed	Without Ketone	With Ketone
0.5NPS/EP-A	10	0.05	1	X		Dispersion	Dispersion
0.5NPS/EP-B	10	0.05	1		X	Dispersion	Dispersion
3NPS/EP-A	10	0.3	1	X		Without Dispersion	Dispersion
3NPS/EP-B	10	0.3	1		X	Without Dispersion	Without Dispersion
5NPS/EP-A	10	0.5	1	X		Without Dispersion	Dispersion
5NPS/EP-B	10	0.5	1		X	Without Dispersion	Without Dispersion
10NPS/EP-A	10	1	1	X		Without Dispersion	Dispersion
10NPS/EP-B	10	1	1		X	Without Dispersion	Without Dispersion

Table 1 NPS/EP composites formulation

Coating characterization

Infrared Spectroscopy (IR-ATR)

Infrared spectroscopy (IR-TF) was used to chemically characterize the coatings. This technique was used to identify the main coating compounds. The spectra were obtained through an ATR-TF Nicolet–iS10 spectrometer, obtaining the average of 16 scans and a resolution of 4 cm–1 with a spectral window of 4000 to 600 cm–1.

Viscosity measurement

The dissolution viscosity was measured using a Brookfield DV2RLV viscometer with UL adapter and TC-650 re-circulator controlling the measurement temperature at 25ºC.

Adherence measurement: Pull of Test

Adhesion tests were performed using PosiTest AT-A equipment. This equipment evaluates the adhesion of a coating based on the critical tensile strength recorded at the time the coating peels off the substrate; the equipment design and test are based on ASTM D4541, D7234 and ISO 4624.

Dispersion of Nanoparticles in the Polymeric Matrix

The dispersion of silica nanoparticles is observed by scanning electron microscopy using a JOEL-6510 plus Scanning Electron Microscope (SEM). In the equipment, the samples are placed on a graphite ribbon without coating of gold to be observable at 500X.

Galvanic corrosion test by gravimetric method

Corrosion tests were performed in accordance with ASTM-B117, using a simulated saline environment with NaCl at 5% by weight as the corrosive agent. A-36 steel specimens with and without coatings were exposed to the corrosive medium using the DIT-105 Peaktech corrosion test bench. The specimens were exposed to a constant current of 0.5A for 90 minutes. At the end of this period, the mass loss caused by corrosion was recorded and the corrosion rate was determined using Eq. 2.

$$V_c = \frac{\Delta m}{A * t} [=] \frac{kg}{m^2 \cdot s} \quad (2)$$

Results

Effect of particle concentration on the viscosity and distribution of NPS on the polymer matrix

Figure 2 shows the effect of the concentration of silica nanoparticles against the viscosity of the formulation, without addition of acetone the observed behavior was exponential, thus the addition of 0.5% of particles increases the viscosity of the resin by 36%; while the addition of 3% of particles increases the viscosity by 541%. Therefore, without solvent, adding these percentages of additive generates slurries difficult to apply and spread on the metal surface. Thus, formulations with nanoparticles containing percentages equal to or higher than 3% are impossible to apply on the substrate to form a thin and homogeneous layer.

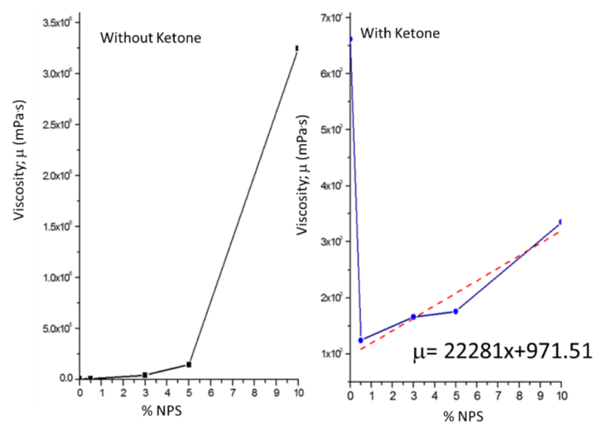

Figure 2 Effect of the NPS concentration on composite

The addition of acetone to the formulations improves the dispersion of the particles in the polymeric matrix, so that the viscosity of the resin decreases and increases linearly with the silica content. Applying a linear regression, a linear determination coefficient of R2=0.9395 was obtained. Table 2 shows the percentages of viscosity decrease in the formulations studied, according to the linear behavior in the viscosity of these formulations, theoretically the viscosity of the resin (6614 mPa–s) is aligned with one loaded with 24% of nanoparticles adding acetone as solvent.

	Viscosity, μ (mPa–s)	% Diminish
Epoxy Polymer	6614	
0.5NPS/EP-A	1242	81.22
3NPS/EP-A	1658	74.93
5NPS/EP-A	1758	73.42
10NPS/EP-A	3350	49.34

Table 2 Viscosity decrease in NPS/EP with acetone addition

Figure 3 shows both low- and high-resolution scanning electron microscopy, comparing a coating formed only with epoxy resin, a commercial automotive anti-corrosion paint and the low silica content coatings of 0.5% (0.5NPS/EP-A) and the high silica content of 10% (10NPS/EP-A).

According to the image observed at low magnification (30X), the resin alone and with 0.5% silica form coatings with good covering capacity that preserves the initial roughness of the metal surface; however, the composite with high NPS content forms a structure with high roughness due to the formation of NPS agglomerates.

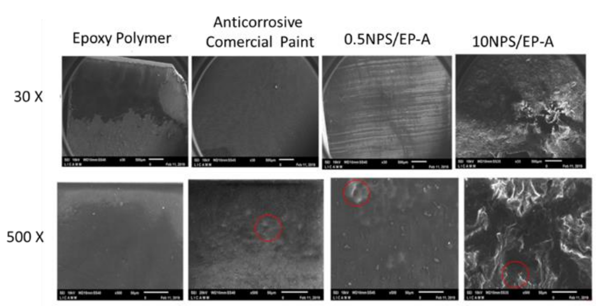

Figure 3 NPS dispersion into epoxy resin

ATR-IRFT NPS/EP Characterization

To determine the stability of the polymer resin with the silica nanoparticles, the spectra of the starting materials (aerosil or silica nanoparticles) and the epoxy resin after curing were obtained. The sum of these spectra results in the theoretical spectrum for NPS/EP (Figure 4). Where it shows that in the composites the signals corresponding to the polymer should be mostly retained and the band corresponding to the siloxane bonds of the silica is retained at 1100 cm^{-1}.

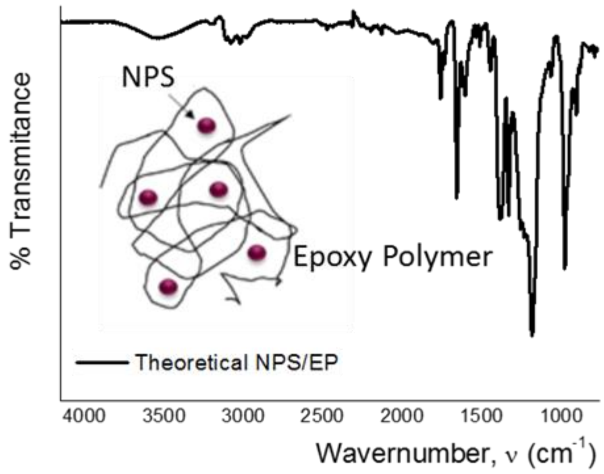

Figure 4 Theoretical ATR-FTIR for NPS/EP

Figure 5 shows the experimental plots obtained for the composites containing 0.3 to 10 % of nanoparticles with the addition of acetone as solvent. It can be observed that the silica nanoparticles are distributed in the polymeric matrix, this is determined according to the peaks of the spectra as they approach those of the aerosil (signal at 1000 cm–1) which indicates that the silica was perfectly integrated in the polymeric matrix. On the other hand, the experimental plots are very similar to the corresponding one for the theoretical composite reflecting that there is no interaction between the additive and the matrix that is causing the decomposition of the material.

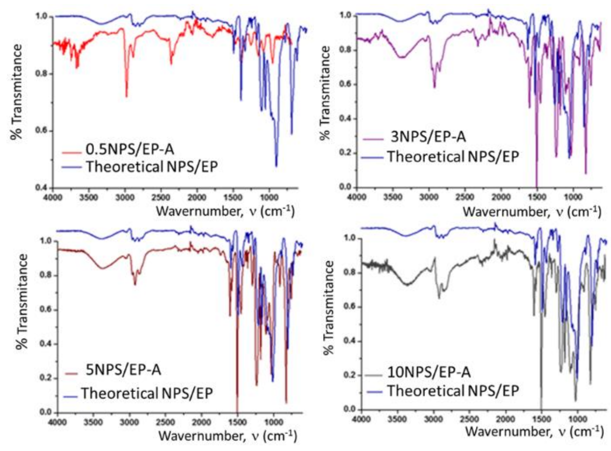

Figure 5 FT-IR for NPS/Epoxy Polymer

Adherence characterization

Among the most important physical properties to be evaluated in a coating is adhesion. This property is measured through the tensile stress required to achieve the detachment of the coatings. For these coatings, the required tensile stress reached 3 MPa for the nanoparticle-free epoxy resin coating. According to Figure 6, higher silica content increases the adhesion of the coatings, thus, the 0.5NPS/EP-A requires an average tensile stress to detach the coating of 3.62 MPa, while increasing the silica content to 10% (10NPS/EP-A) requires a tensile stress of 5.1 MPa to achieve the detachment of the deposited coating.

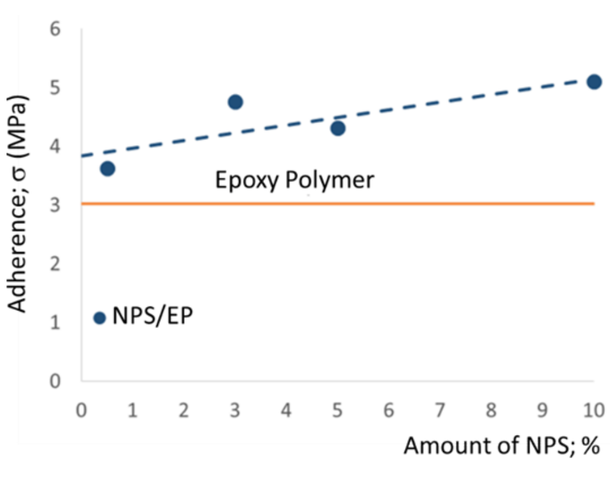

Figure 6 Adherence for NPS/EP

NPS/EP anticorrosion behavior

The anticorrosive performance of the coatings is determined from the corrosion rate values. These values are compared with the NACE (National Association of Corrosion Engineers) international criteria is specified in Table 3 (McCafferty E, 2010).

According to the results shown in Figure 6, the polymer resin has a poor corrosion resistance, since a corrosion rate of 107 MPY was obtained, while the A-36 steel presented a corrosion rate of 52.6 MPY having an acceptable corrosion resistance.

Corrosion Resistance	Corrosion Rate (MPY)
Extraordinary	<1
Excellent	1-5
Good	5-20
Admissible	20-50
Poor	50-200
Unacceptable	>200
*MPY= mils per year	

Table 3 Relative severity of corrosion rates

When silica nanoparticles were added, a significant improvement in the corrosion resistance of the polymer was observed, with corrosion resistance values ranging from good to outstanding. The composites with 0.5% silica and 5% silica showed good corrosion resistance with corrosion rates Vc of 7.08 and 13 MPY respectively. While the 10NPS/EP-A (10% silica) had excellent corrosion resistance with a corrosion rate Vc=1.42 MPY. Finally, the coating with 3% silica behaved as an outstanding corrosion protective barrier showing a corrosion rate of 0.472 MPY.

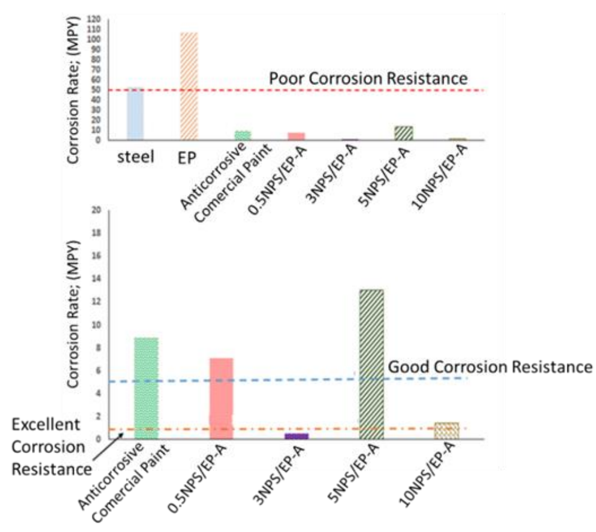

Figure 6 Corrosion rate for NPS/EP-A

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Conclusions

According to the results obtained in the tests carried out, it is concluded that silica is a good anticorrosive agent, in addition to the fact that it especially increased the properties and parameters that were measured in this project, such as adhesion (19 to 68%) and corrosion resistance (from poor to extraordinary).

The coating that showed the best results in the tests carried out was the coating with 3% silica using acetone as solvent.

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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).

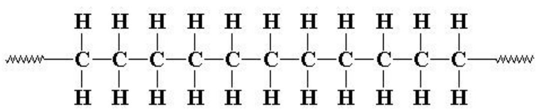

Figure 1 Atomic composition of polyethylene
Source: (Coreño & Méndez, 2010).

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.

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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).

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.

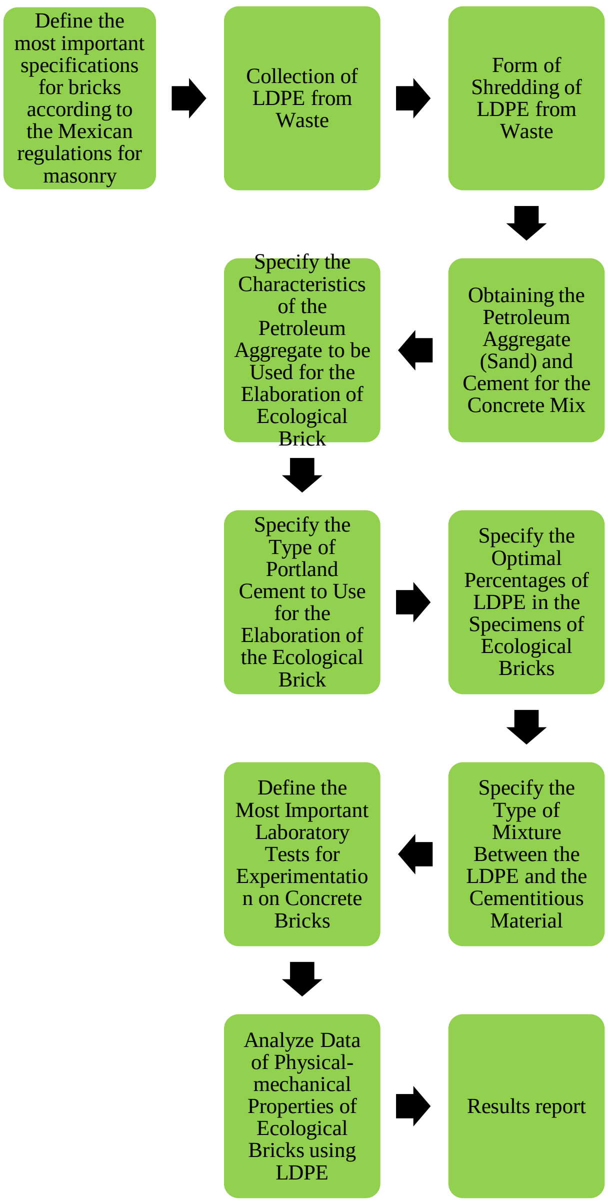

Figure 4 Flowchart with order of activities to be carried out for the research project

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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Article

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Implementation of a neural network of low computational cost for its application in arm prostheses

Implementación de una red neuronal de bajo coste computacional para su aplicación en prótesis de brazo

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Abstract

A prostheses implementation represents a design challenge in its different stages. The control systems and the total system cost play a very important role. In this work, a control proposal is presented using artificial neural networks (ANN) for pattern recognition using electromyographic (EMG) signals, which are obtained from the arm muscle (biceps). A single channel EMG surface sensor is used to acquire the EMG signals and by means of adjacent windows the feature extraction is carried out in order to reduce the input values to the neural network. The neural network is trained with the features extracted from the EMG signals, using a method of muscle tension thresholds for activation and a labeling technique for the output called One Hot Encode. The resulting ANN was embedded in a low-cost microcontroller and an accuracy of approximately 93% was achieved.

Pattern recognition, Neural networks, Surface EMG sensor

Resumen

El polietileno de baja densidad (LDPE), se encuentra La implementación de una prótesis representa un reto de diseño en sus diferentes etapas. Los sistemas de control y el coste total del sistema juegan un papel muy importante. En este trabajo se presenta una propuesta de control mediante redes neuronales artificiales (RNA) para el reconocimiento de patrones utilizando señales electromiográficas (EMG), que se obtienen del músculo del brazo (bíceps). Se utiliza un sensor de superficie EMG de un solo canal para adquirir las señales EMG y mediante ventanas adyacentes se realiza la extracción de características para reducir los valores de entrada a la red neuronal. La red neuronal se entrena con las características extraídas de las señales EMG, utilizando un método de umbrales de tensión muscular para la activación y una técnica de etiquetado para la salida denominada One Hot Encode. La RNA resultante se incrustó en un microcontrolador de bajo coste y se consiguió una precisión de aproximadamente el 93%.

Reconocimiento de patrones, redes neuronales, sensor EMG de superficie

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Introduction

Myographic signals have played a very important role in the design and implementation of gesture classification systems and prosthesis implementation. Prostheses require control systems that allow the user to perform basic tasks such as those performed by the real member (Oziomek et al., 2022; Polo Hortigüela, 2022). The synergy between the control system and the myographic signals should provide an accessible and economical methodology in the implementation. A methodology that has been recently used in the literature consists of the characterization of gestures through the use of myographic signals and Artificial Neural Networks (ANN) (Talib et al., 2019). In recent decades, artificial neural networks have become popular as a control method due to their advantages in efficiently and effectively modeling complex problems. Neural networks can find relationships or patterns inductively through learning algorithms, based on the data that the user specifies (Asghari Oskoei & Hu, 2007). The combination of tools such as neural networks and the acquisition of myographic signals has provided control systems for limb prostheses. EMG signals are rich in information, which is used by neural networks to generate control signals, but they usually require a high consumption of computational resources that complicate the implementation of lightweight and portable models(Zhang et al., 2019a).

On the other hand, the extraction of the characteristics of the EMG signals is a methodology that allows to know certain information about the signal. Features can be time domain (TD), frequency domain (FD), or time-frequency domain (TFD). However, the best performing data for neural networks is in the time domain (Zhang et al., 2019b). Most of the gesture prediction models are based on the use of sensors for EMG signals that require a large number of channels, which translates into higher cost and complexity of the system (S. Ahmed et al., 2020). Surface electrode EMG sensors are safe and easy to use. Although surface electrodes provide a better approximation of superficial muscle activity, they cannot be used to detect selective signals from small and deep muscles due to the problem of crosstalk. Even signals from superficial muscles are contaminated by crosstalk from muscles adjacent to and below the target muscle (Aljobouri, 2022).

The application of a microprocessor for the control of myoelectric signals has advantages of both functionality and cost. In addition, to adapt easily, which translates into a greater responsiveness. Pattern recognition-based control increases the variety of control functions and increases robustness (Amato et al., 2013; Antonelli et al., 2022).

In this work, we propose a pattern recognition control model based on EMG signals of the biceps muscle. For data acquisition, we used a DFROBOTS EMG Gravity sensor to identify three voltage thresholds. For signal processing, we use the extraction of temporal characteristics using the most representative ones such as the mean absolute value (MAV), the root mean square (RMS) and the wavelength of the waveform (WL) (Artemyev & Bikmullina, 2020; Barandas et al., 2020). An Arduino Nano board was chosen for its size and flexibility. For the classification we applied the labeling technique called One Hot Encoding and the artificial neural network was trained in Matlab.

Materials

An analog electromyographic (EMG) sensor of the DFROBOT brand, shown in figure 1, was used for the experiments. It consist of a single-channel sensor that has two plates. One of the plates is a metallic surface contact electrode that is attached to the arm by means of an elastic band and the other is the part of the interface between the electrode and the Arduino Nano board. The main advantages of this sensor compared to other EMG sensors is that its electrode is not like conventional suction suckers that adhere to the skin by glue and/or conductive liquid, so it is not necessary to replace the electrodes frequently. The EMG sensor electrode was placed on the biceps since this muscle will have the function of activating the prosthesis (Cote-Allard et al., 2019).

Figure 1 Analog EMG sensor
Source: dfrobot.com

The microcontroller used is an Arduino nano, as shown in figure 2. This board is based on the ATmega328P microcontroller, with an operating frequency of 16 MHz. According to the manufacturer's specifications, sampling frequencies of 10 KHz can be achieved, which is sufficient for the activity to be carried out.

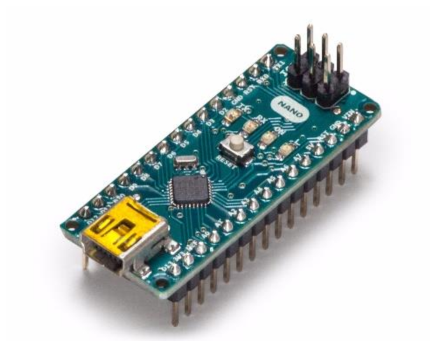

Figure 2 Arduino nano
Source: Arduino community

Data Adquisition

Through the EMG sensor, the necessary tests are carried out and the data that will be processed later in an artificial neural network is stored. In this work three levels of tension are distinguished that will be processed and classified by the ANN. For the implementation of a pattern recognition ANN, a training phase is required where the data to be learned and the category to which it must be assigned are presented. Then, for the first stage, the EMG signals from the biceps are sampled at three voltage thresholds (Cote-Allard et al., 2019; Hagengruber et al., 2022; Setioningsih, 2021). Figure 3 shows the thresholds distinguished by vertical dotted lines, on the left “low voltage”, in the middle “medium voltage” and on the right “high voltage”. Sampling was done at 100 Hz, in other words, one sample every 10 ms.

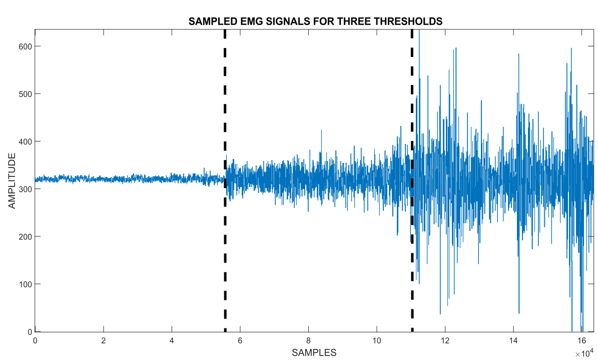

Figure 3 Sampled EMG signals for three thresholds
Source: Own elaboration

For the processing of the input signals, the temporal characterization of the signal was applied. The data was separated into separate windows of fifty values and the mathematical formulas for the time domain characterization were applied. The most representative characteristics are the mean absolute value (MAV), the root mean square (RMS) and the waveform length (WL) (S. S. Ahmed et al., 2021; Lee et al., 2021).

$$MAV = \frac{1}{N}\sum_{n=1}^{N} |x_n| \quad (1)$$

$$RMS = \sqrt{\frac{\sum_{n=1}^{N} x_n^2}{N}} \quad (2)$$

$$WL = \sum_{n=1}^{N} |x_n - x_{n-1}| \quad (3)$$

Having the input data for training the neural network, it is necessary to determine the classes to classify. For the output classes we use a labeling technique called “One Hot Encode”, as shown in Table 1 (Samuel et al., 2019; Witman et al., 2019). This technique consists of proposing a vector of size equal to the number of thresholds of the input signal, in this case the vector is of size three since that is the number of thresholds to classify. The characteristic of this vector is that it has only one value equal to one and the rest are zero.

One Hot Encode			Threshold value
0	0	1	Low muscle tension (S1)
0	1	0	Medium muscle tension (S2)
1	0	0	High muscle tension(S3)

Table 1 Labeling the One Hot Encode output classes
Source: Own elaboration

Implementation of the ANN

For the implementation and training of the ANN, Matlab was used. First, the data is preprocessed using standard normal normalization. When we refer to the data, we are talking about the temporal characteristics MAV, RMS and WL, respectively. With the preprocessed input data and the output classifications, a neural network is proposed that will have three inputs, two neurons in the hidden layer and three neurons in the output layer. The activation function for the proposed hidden layer is known as Poslin (Positive Linear), also known as ReLu (Lin Wang & Buchanan, 2002). The behavior of the ReLu function is shown in Figure 4.

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$a = 0 \quad n < 0$ $a = n \quad 0 \leq n$	

Figure 4 ReLu activation function range and symbol
Source: Neural Network Design 2da edition.

For the activation function of the output layer, the Softmax function was used, expressed in equation (4). The characteristic of this function is that a probability value is determined for each of the outputs, where the element of the vector with the highest value in probability is corresponding to the estimated output, in addition, it must be fulfilled that the sum of the probabilities of all its elements of the vector equal to one (Chambon et al., 2018; Nam et al., 2022).

$$\sigma(\vec{z})_i = \frac{e^{zi}}{\sum_{j=1}^{k} e^{zj}} \quad (4)$$

The structure of the pattern recognition neural network is shown in Figure 5. The network consists of three inputs, two neurons in the hidden layer and three neurons in the output layer.

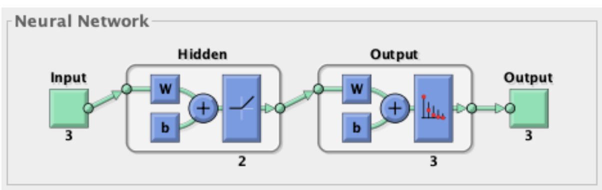

Figure 5 Structure of the neural network
Source: Own elaboration

Results

The results obtained from the training of the neural network show that the network can achieve the tolerable error reduction after 115 training epochs. Figure 6 shows the cross-entropy behavior of the training data, the validation data, and the test data during execution. It can be observed that the cross entropy tends in all cases to the best performance, which implies that the error approaches a relatively low value, close to zero.

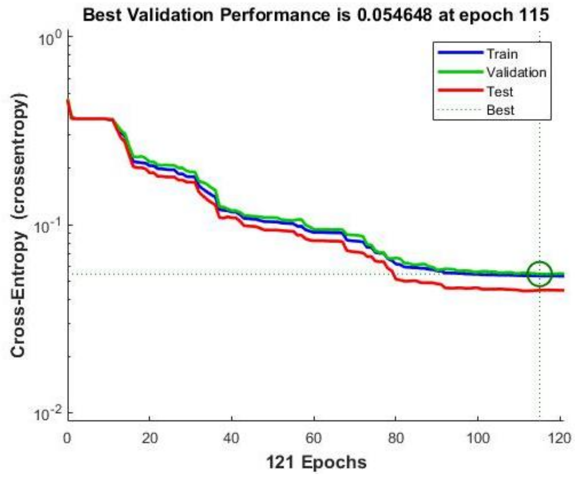

Figure 6 Performance validation
Source: Own elaboration

Figure 7 shows the confusion matrix for the training data of the neural network. In this matrix, the cases of detection (correct or incorrect class) of the input signal that can be obtained by the neural network are grouped. At this stage, 93.8% accuracy is achieved. This indicates that the training data globally provide an adequate precision in the classification of muscle tension levels.

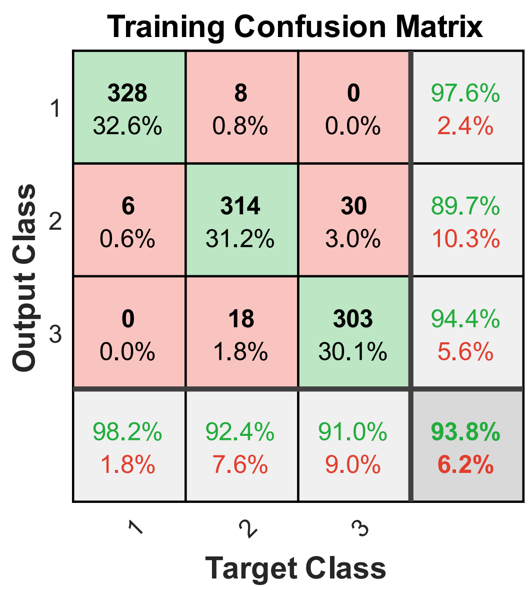

Figure 7 Confusion matrix of the training values
Source: Own elaboration

As shown in Figure 8, the confusion matrix for the validation data reaches 93.1% detection accuracy. Validation allows us to see the capacity of the network for data that was not used in the training and adequate precision is observed.

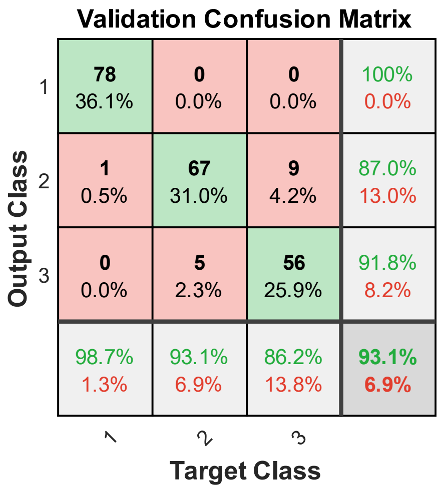

Figure 8 Confusion matrix of validation values
Source: Own elaboration

The confusion matrix indicated in figure 9 for the test data, reaches a 94% correct detection. Note that the test data is reserved for testing the already trained network. This result shows that the trained network offers excellent accuracy on new data.

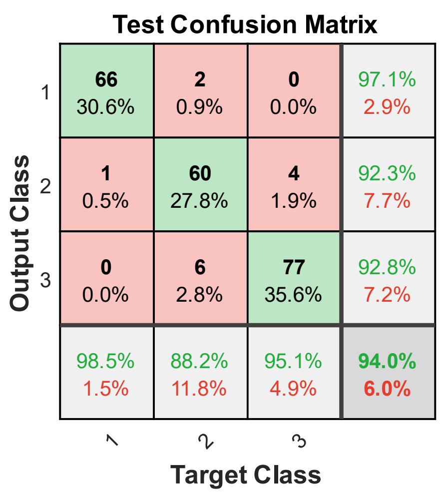

Figure 9 Confusion matrix of test values
Source: Own elaboration

Lastly, the general confusion matrix shown in figure 10 shows the general average of RNA detection, with a precision of 93.7%, which implies a detection of errors of 6.3%, which is sufficiently low.

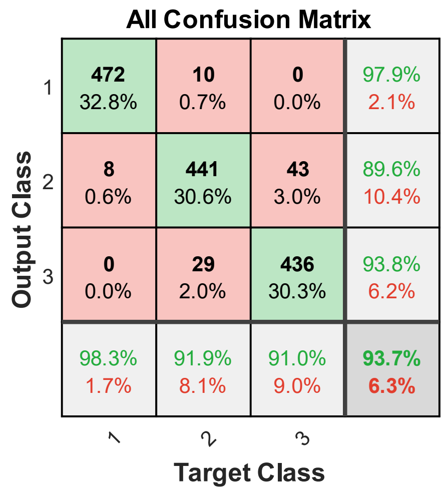

Figure 10 Confusion matrix of the general average of the values
Source: Own elaboration

The error histogram in Figure 11 is a graph that groups the cases by their variability of error obtained. It is observed that the maximum of the graph is very close to zero, which implies that the behavior of the error, in this network, is low enough, allowing an adequate detection.

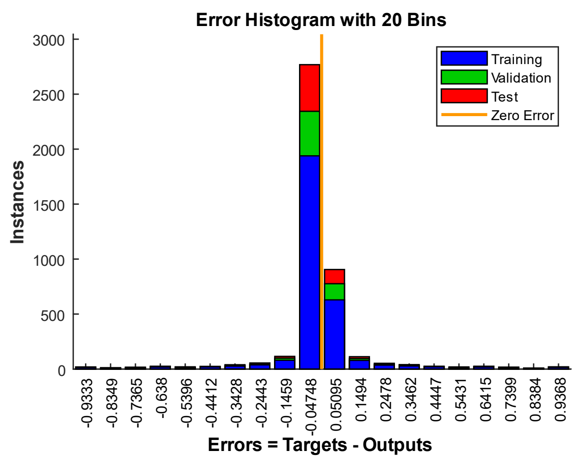

Figure 11 Error Histogram
Source: Own elaboration

On the other hand, equations (5), (6), (7) and (8) represent the weights corresponding to the hidden layer, the layer weights of the output layer, the biases of the hidden layer and the biases of the output layer, respectively.

$$W1 = \begin{bmatrix} -0.926 & 1.81 & 1.292 \\ -0.492 & 2.761 & 0.566 \end{bmatrix} \tag{5}$$

$$w2 = \begin{bmatrix} -1.51 & -7.614 \\ -3.178 & 1.95 \\ 1.903 & 0.692 \end{bmatrix} \ldots. \tag{6}$$

$$b1 = [0.974 \quad 2.564] \tag{7}$$

$$b2 = [4.501 \quad -0.76 \quad -3.001] \tag{8}$$

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These weights and biases are used to implement the trained neural network within any microcontroller, in this case an Arduino Nano. Figure 12 shows the block diagram for the implementation.

Figure 12 Block diagram for implementation
Source: Own elaboration

Conclusions

An artificial neural network was trained and an accuracy of 93.7% was achieved for an application with electromyographic signals. The network inputs were obtained from the signal produced by an EMG sensor and the extraction of the MAV, RMS and WL temporal characteristics. The use of the temporal characteristics allows to obtain a good enough precision for this application, this small ANN with only two input neurons in the hidden layer and three output neurons requires a low computational cost and can be easily implemented in an Arduino Nano.

One of the problems faced by this proposal is the limitations due to crosstalk caused by the adjacent muscles of the biceps, which could be reduced by increasing the number of electrodes of the EMG sensor.

artificial neural network fulfills its purpose, being cheap to implement compared to other more sophisticated systems, in addition to its low energy and computational cost.

Regarding EMG control, it is recommended that the user carries out muscle therapies and exercises in the area to improve the quality of muscle signals, in such a way as to facilitate control of thresholds and prolong the time of use of the sensor. The system could cause muscle fatigue when used for long periods of time.

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Numerical study of the influence of the micro pin fin arrangement on the thermal and hydraulic performance of a micro heat sink

Estudio numérico de la influencia del arreglo de las micro aletas en el desempeño térmico e hidráulico de un micro disipador de calor

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Abstract

In this project, a numerical study of the thermal and hydraulic performance in a micro pin fin heat sink is carried out. The micro heat sinks pin fins are used for cooling of electronic, due that every day a more powerful and smaller chips and electronic components are required. The geometric parameters to the build of the heat sink with micro pin fins are chosen in base of the geometric needs of the electronic chip, a circular geometry is used for the micro pin fin and inline and staggered arrangement for the micro pin fins distribution is used, different velocities in the inlet of the heat sink are used for development of the study. In the result section, the temperature contours and the thermal resistance of the different cases analyzed are reported, as well as the pressures distributions and the total pressure drop along the heat sink micro pin fin are reported too. Taken account the results, the optimal geometry for thermal and hydraulic performance of the heat sink micro pin fin is obtained.

Heat sinks, Micro pin fins, Thermal resistance, Pressure drop

Resumen

En el presente proyecto se realiza un estudio numérico del desempeño térmico e hidráulico de un micro disipador de calor con micro aletas. Estos disipadores son usados en el enfriamiento de chips electrónicos, ya que día con día se tienen chips más potentes y pequeños. En base a las necesidades geométricas del chip electrónico se eligen los parámetros geométricos para la construcción de la geometría del disipador de calor con micro aletas, se utiliza la geometría circular para las micro aletas, se usa el arreglo en línea y el escalonado para la distribución de estas. Se utiliza agua como fluido de enfriamiento, se hace el análisis para diferentes velocidades de entrada del fluido. Dentro de los resultados reportados están los contornos de temperatura y la resistencia térmica de los diferentes arreglos de las micro aletas, así como también la distribución de presión y la caída de presión total a lo largo del disipador, esto para diferentes números de Reynolds. Tomando en cuenta los resultados se elige la geometría óptima para el mejor desempeño térmico e hidráulico del disipador de calor con micro aletas.

Disipadores de calor, Microaletas, Resistencia térmica, Caída de presión

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Introduction

Over the years there have been important technological contributions in the area of electronic devices, which has required electronic circuits with increasingly better performance and greater energy efficiency, as well as the reduction of noise during operation; In addition to this, their size has also been required to be smaller and smaller, reaching measurements of micrometres and sometimes even nanometres, to meet the needs of the consumer, as more powerful and faster systems are required, but also smaller and lighter, which is more comfortable for the user, especially in portable devices such as mobile phones, computers, tablets, etc.

The use of very small electronic chips has brought an important problem to solve, which is the generation of hot spots in these devices, these spots are generated because the designs are complex and the power distribution within the chips is often not adequate, resulting in the generation of these hot spots, which produce high temperatures, which in turn reduce the performance and life of the chips and in most cases irreparable damage to them.

To solve these heating problems, it is of utmost importance to incorporate cooling systems to electronic chips, but due to their design and the amount of heat generated inside them, conventional cooling techniques based on forced convection through air are not enough, due to the size of the microprocessor, so new cooling techniques must be used, one of these techniques is liquid cooling through microchannels.

In the early 2000s, (S. G. Kandlikar, 2005) proposed different scenarios in which the technique of liquid cooling by means of microchannels is applied to electronic devices, resulting in this being the best cooling technique, especially when working with heat flows greater than 100 W/cm^2.

This technique has been improved over the years, micro fins have been implemented in many occasions instead of microchannels, which have been studied with different geometric configurations, offering improvements in heat transfer increases according to the geometry of the micro fin used; Similarly, different types of microfin arrangements have been tested, such as in-line and staggered arrangements, and different types of cooling fluids have been used, with nanofluids being one of the best options to increase heat removal.

Background

The first record of the use of liquid cooling by means of microchannels is reported by (Tuckerman & Pease, 1981), who implemented microchannels in a heat sink and used water as a cooling fluid, they managed to dissipate a heat flow of up to 790 W/cm^2, which acted constantly on the surface of the heat sink.

In their work (S. Kandlikar et al., 2005), they publish on fluid mechanics and heat transfer in mini-channels and microchannels analysed under a single phase, they provide the theoretical basis for this type of analysis, as well as some correlations for the calculation of the pressure drop and the convective coefficient of heat transfer. In another paper (S. G. Kandlikar, 2005), he describes how by using microchannels it is possible to dissipate heat fluxes of up to 1 kW/m^2.

Since then, the use of microchannels has increased considerably, especially in applications where a large amount of heat flow must be removed and the space to install heat sinks is very small. To improve this technique, the use of mini and micro fins has been employed to increase heat transfer, with good results in terms of thermal performance so far.

Numerical analyses have been developed to investigate the performance of micro finned heat sinks, different micro fin geometries and different type of cooling fluid have been analysed, for example, (Saravanan & Umesh, 2018), compared the fluid flow and heat transfer characteristics for a micro finned heat sink and the microchannel heat sink without fins. They used a constant heat flux of 10 W/cm^2, for Reynolds numbers between 100 and 900. Square and circular micro fins, with an in-line and staggered arrangement, are considered.

The results indicate that the finned heat sink has a higher Nusselt number and friction factor. The micro-fin geometry that offers the best heat transfer is the square fin. Also, the finned heat sink has a better thermal performance index compared to the microchannel-only heat sink and is more preferable when heat dissipation is compared to the pressure drop penalty.

On the other hand, (Karami et al., 2019), perform a numerical simulation of a heat sink with micro fins and placing a baffle for a water flow for a range of 50≤Re≤250. They investigate the type of baffle and its dimensions, with this they find out the effects of it on the overall performance of the heat sink. The baffles they used are single, double and triple segment baffles, with four different overlaps, classified as 60%, 40%, 20% and 0%. Their results compare them with a micro-fin heat sink without baffles. In their results they show that the use of fin baffles increases the heat transfer, but also increases the pressure drop. The heatsink with a 20% overlapping double segment baffle has the highest heat transfer.

(Alam et al., 2020), perform a numerical analysis to investigate the behaviour of a triangular micro-finned heat sink used in a central processing unit (CPU), they report the heat transfer and pressure coefficient for different Reynolds numbers. In their work they consider the effects of turbulence intensity in the system. Similarly, (He et al., 2021), propose a heat sink with ribbed micro fins, which they compare with a smooth microchannel and circular micro fins with an in-line arrangement. In their results they report an increase in the Nusselt number when using the ribbed fins, resulting in almost a two-fold increase compared to circular microfins with an in-line arrangement and three times more compared to a smooth microchannel. This results in better thermal performance.

(Gupta et al., 2021), study the hydrodynamic and thermal characteristics of a heat sink with perforated micro fins, the micro fins are of different shape and the number of perforations also vary. The results they report show that heat sinks with perforated micro fins provide higher Nusselt number values and lower pressure drop levels than with non-perforated micro fins. These perforations have also shown a higher efficiency of the micro fins compared to non-perforated micro fins. In addition, when perforations are used, the performance is superior to non-perforated ones. The shape of the perforation is also analysed, resulting in a circular shaped perforation being more efficient, followed by elliptical and square perforation.

Experimental analysis includes work by (Kewalramani et al., 2019), who analysed the hydrothermal characteristics of a micro heatsink with elliptical micro fins with a constant heat flux over the base of the heatsink. They performed experiments on the heatsinks using deionised water as the cooling fluid. They developed a numerical model for a single-phase incompressible laminar flow and validated it with experimental results. In their results they find that the behaviour of the local heat transfer coefficient. They propose a length scale selection criterion to define the Reynolds number, the Nusselt number and the friction factor and develop correlations describing the behaviour of the Poiseuille number and the Nusselt number with respect to the Reynolds number and the Prandtl number. These correlations can be useful in the design of elliptical micro-fin heat sinks.

In the area of micro finned heat sink optimisation, models have been developed to predict the pressure drop behaviour, (Lee et al., 2021), develop an artificial neural network to predict the thermal and hydrodynamic performance of finned micro heat sinks used in high heat flux electronic devices. They use a wide variety of geometric, operating and hydraulic performance conditions to train the artificial neural network as accurately as possible. Their results are compared with correlations based on the regression method, obtaining superior performance with their model. Other optimisation studies are developed by (Chen et al., 2017), who carry out the optimisation of finned micro heat sinks using contract theory and minimum entropy generation.

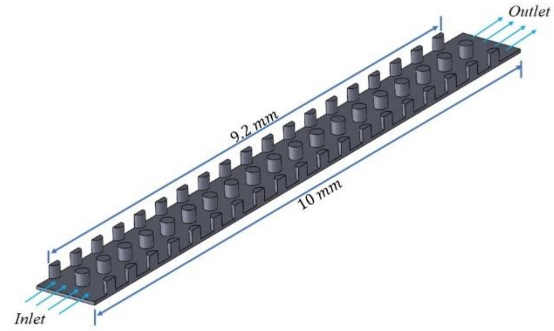
With this optimisation technique, the influence of material, heat transfer and fluid velocity will be taken into account, which represents a more complete analysis. In their results they report the optimal diameters for the fins. For the formulation of their objective function they take into account the geometrical parameters and the number of fins, determining the influence of material, heat transfer and fluid velocity on the results.

In this work a micro heat sink with micro fins is analysed, which have a circular geometry, in line and staggered arrangements are considered for the micro fins, a configuration for the staggered arrangement is proposed, which consists of the micro fins that are deflated having a different diameter to the non deflated fins, this with the aim of not affecting the pressure drop to a large extent. The cooling fluid used is water at 293 K. The material of which the heat sink is made is silicon and a constant heat flow is applied to the base of the heat sink.

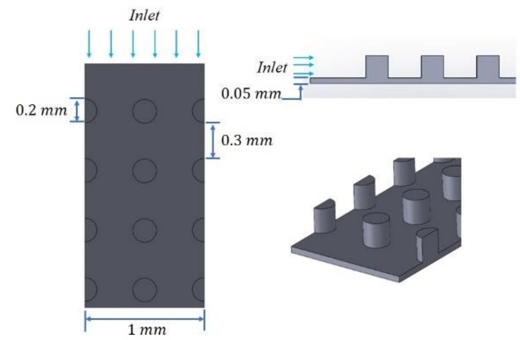
Geometry

For the analysis of the micro heat sink with micro fins, we start from the construction of the geometry to be studied, for this construction we make use of the symmetry tool, that is, we will take only one area of interest, which represents what happens in the complete domain to be analysed, with this we will save time and computational resources.

Figure 1 shows the segment of the heat sink with micro fins being analysed, the geometry of the micro fins used is circular, the dimensions of the micro fins and the heat sink are shown in the figure. It can be seen how the symmetry condition is taken, in order to simplify the computational model. The arrangement depicted in Figure 1 is the in-line arrangement for the micro fins.



a)



b)

Figure 1 Geometry of the heat sink with micro fins considered for numerical analysis. a) Heatsink and b) top, side and isometric views
Source: Own elaboration.

Figure 2 shows two of the arrangements analysed for the placement of the micro fins, a) shows the in-line arrangement, which is the arrangement commonly used for forced convection heat sinks using air. (b) shows a staggered arrangement, which causes a row of micro fins to be placed in the middle of the flow line, forcing the flow to have directional changes along its flow line. S_T represents the transverse spacing between the micro fins and S_L the longitudinal spacing, which for the analysis cases are both 0.5 mm.

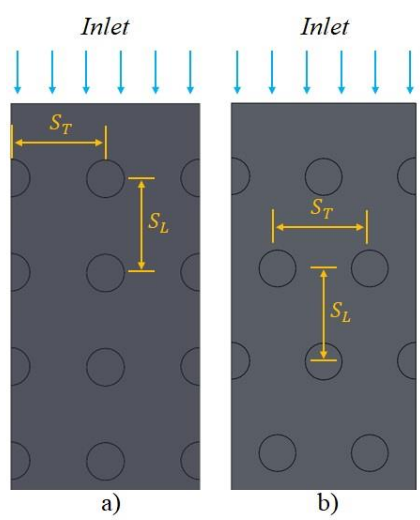


Figure 2 Arrangement of the micro fins on the heat sink. a) in-line arrangement and b) staggered arrangement
Source: Own elaboration

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Figure 3 shows the arrangement of the micro fins proposed in this research, which is based on the arrangement proposed by (Bello-Ochende & Bejan, 2005), who used this arrangement to increase natural convection heat transfer by using cylinders of various sizes and optimally placed. In a cylinder arrangement, they place smaller cylinders at the entrance of the assembly, so that the smaller cylinders occupy the space that is not used for heat transfer. Although this arrangement is used in natural convection, it is being studied to investigate its performance under forced convection in micro-finned micro heat sinks.

For this arrangement we have to combine different diameters of the microfins, following the ratio Ø_o⁄Ø_1, thus the first row of fins corresponds to the diameter Ø_o (larger diameter) and the second row to the diameter Ø_1 (smaller diameter), as can be seen in Figure 3 b). The transverse and longitudinal spacing is the same as for the staggered arrangement.

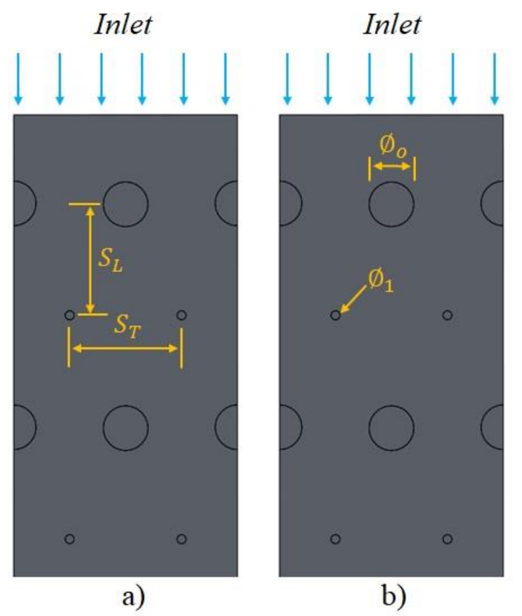

Figure 3 Arrangement of the micro fins on the heat sink
Source: Own elaboration

Case	Arrangement	$\emptyset_o/\emptyset_1$
1	In line	Not applicable
2	Staggered	1
3	Staggered	0.8
4	Staggered	0.6
5	Staggered	0.4
6	Staggered	0.2

Table 1 Cases of the different geometrical models analysed for the different arrangements
Source: Own elaboration

Table 1 shows the different cases analysed in this study, in Case 1 an in-line array is analysed, in cases 2 to 5, geometric staggered arrays are analysed, in which the diameter of the second row is varied as in Figure 3, the ratio of Ø_o⁄Ø_1, from 1 to 0.2, is used.

Computational analysis

A mesh is constructed for the numerical analysis, one of the constructed meshes is shown in Figure 4. It can be observed how the mesh adapts perfectly to the geometry, thus avoiding the generation of negative volumes or areas with a non-uniform mesh.

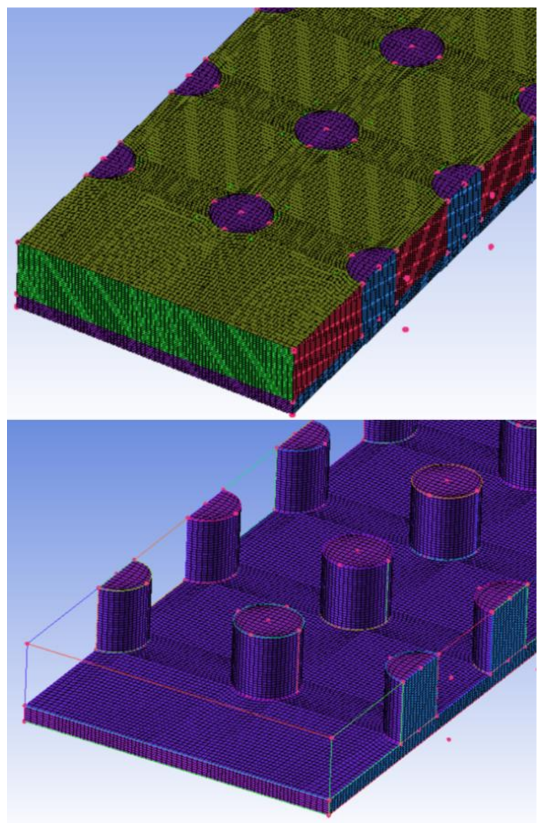

Figure 4 Mesh constructed for numerical analysis
Source: Own elaboration

Graphic 1 shows the mesh sensitivity analysis carried out, it can be seen how the temperature varies with the increase in the number of nodes, until it stabilises and no longer produces any change, with this we can take that the mesh with a number of elements of 1,545,600 is the one that can be taken to carry out the numerical analysis.

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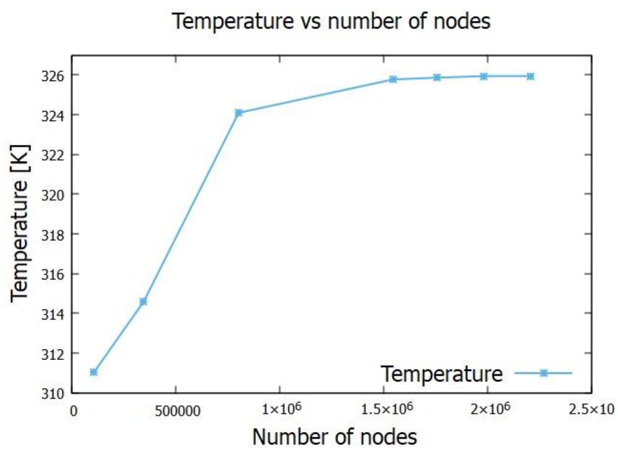


Graphic 1 Change of the temperature at the heatsink base for different numbers of nodes
Source: Own elaboration

Figure 5 shows the boundary conditions used for the numerical simulation, an inlet velocity, an outlet pressure, at the base of the heat sink, the application of a constant heat flow is considered, which is 60,000 W⁄m^2 and the symmetry condition is used on both sides of the geometry, thus reducing the computation time to obtain the results.

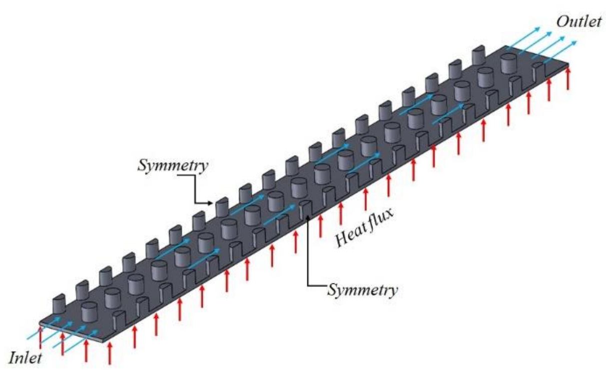


Figure 5 Boundary conditions taken to perform the numerical simulation
Source: Own elaboration

Once the boundary conditions are considered, the following considerations are taken into account:

- Steady state for heat transfer.
- Incompressible flow.
- Constant thermophysical properties.
- Flow in a laminar regime.
- A water fluid inlet temperature of 293 K.
- The heat flux considered at the base of the heatsink is 60,000 W⁄m^2.

The material considered for the numerical analysis of the heat sink with microfins is silicon, because a large number of electronic components are manufactured with this material, and water is used as the working fluid for cooling the heatsink. The thermophysical properties of silicon and water considered for the numerical analysis are presented in Table 2.

Property	Value
Water	
Thermal conductivity (W/mK)	0.5948
Specific heat (kJ/kgK)	4.183
Density (kg/m^3)	997.1
Viscosity (kg/ms)	0.0008905
Silicon	
Thermal conductivity (W/mK)	148
Specific heat (kJ/kgK)	0.712
Density (kg/m^3)	2330

Table 2 Thermophysical properties of the working fluid and the silicon
Source: Own elaboration

The equations governing the analysed phenomenon are: for the fluid, the energy equation (Equation 1), conservation of mass (Equation 2) and the momentum equation (Equation 3).

$$\rho_f C_{pf}\left(\vec{V}\cdot\nabla T\right) = k_f \nabla^2 T \quad (1)$$

$$\nabla\cdot\vec{V} = 0 \quad (2)$$

$$\rho_f\left(\vec{V}\cdot\nabla\vec{V}\right) = -\nabla P + \mu\nabla^2\vec{V} \quad (3)$$

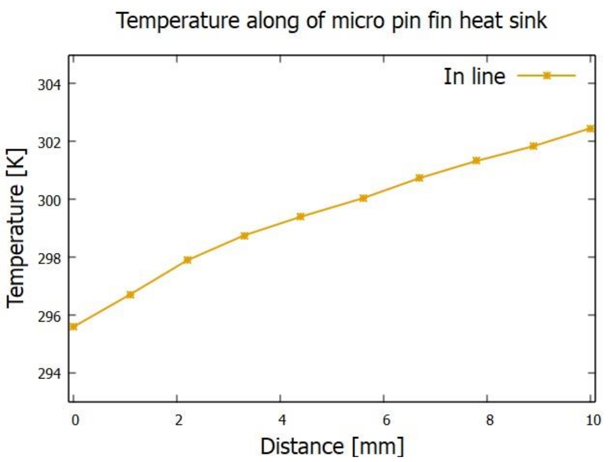
For the micro finned heat sink, only the energy equation (Equation 4) is considered:

$$\nabla^2 T = 0 \quad (4)$$

Results

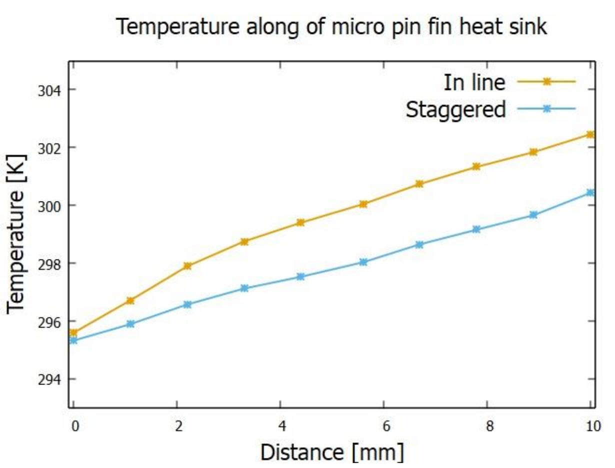
This section shows the thermal and hydrodynamic results of the numerically studied cases, the temperature profiles at the base of the micro-finned heat sink, the temperature and pressure distribution contours along the heat sink, as well as the thermal resistance and the total pressure drop along the micro-finned heat sink.

Graphic 2 shows the behavior of the temperature profile along the heatsink base when using an in-line micro fin array (Case 1), the effect of the cooling fluid on heat removal at the base of the heatsink, the lowest temperature occurs at the inlet of the heatsink and the highest temperature occurs at the outlet, obtaining an average temperature of 299.56 K over the entire surface of the heatsink.



Graphic 2 Temperature at the base of the heatsink with micro fins for a Re = 100
Source: Own elaboration

To observe the effect of the different arrangements of the micro fins on the cooling of the heat sink, Graph 3 shows the comparison of the in-line arrangement and the staggered arrangement, which correspond to Case 1 and Case 2, respectively. It can be seen that the staggered arrangement has a better thermal performance, since it has an average temperature of 297.62 K over the entire surface of the base of the heat sink, which is lower than that of the in-line arrangement.



Graphic 3 Temperature comparison of a microfin heatsink with an in-line array and a staggered array, for Re = 100
Source: Own elaboration

Figure 6 shows the temperature contours along the base of the heat sink for Case 1 and Case 2, it is clearly observed how the lowest temperatures are obtained in the staggered arrangement, it is also observed that there are no heating points, obtaining a uniform distribution along the entire base.

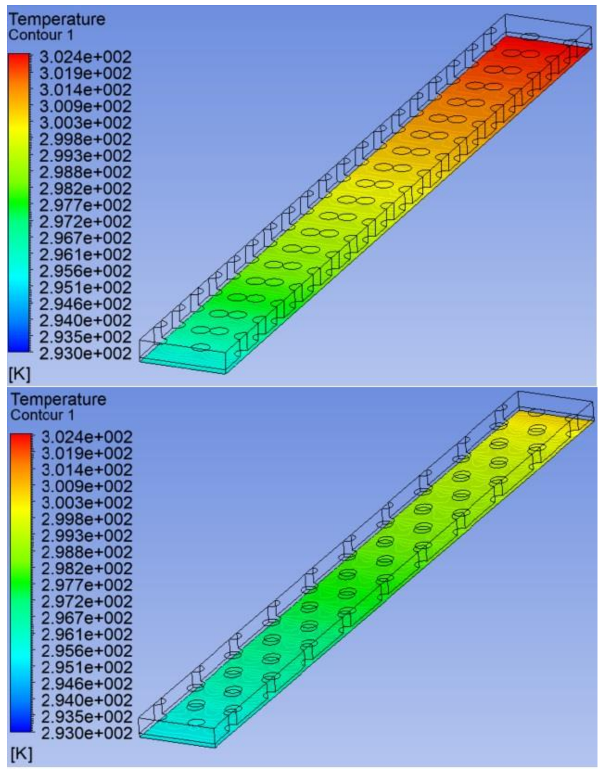


Figure 6 Comparison of the temperature contours of a micro-finned heatsink with an in-line array (Case 1) and a staggered array (Case 2), for Re=100
Source: Own elaboration

One of the parameters that provides information about the thermal performance of the heat sink is the thermal resistance, which indicates how easily heat can be transferred through the heat sink to the fluid and thus removed to the outside. The thermal resistance can be calculated with the following equation:

$$R_t = \frac{T_s - T_{ent,f}}{q''} \qquad (5)$$

Where the variable T_s is taken as the surface temperature of the heatsink base, T_(ent,f) is the temperature at which the cooling fluid enters the heat sink and q" is the heat flux supplied at the base of the heatsink.

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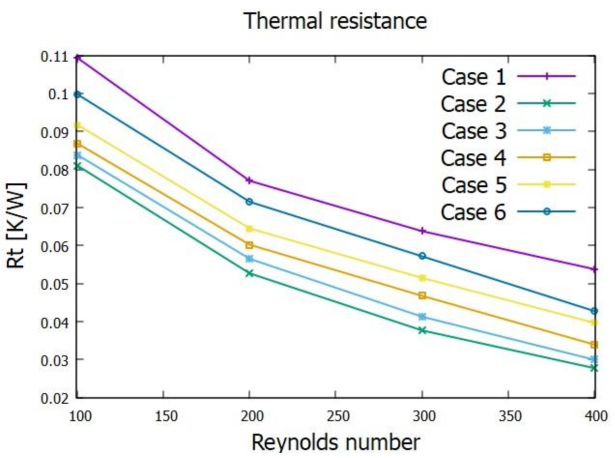
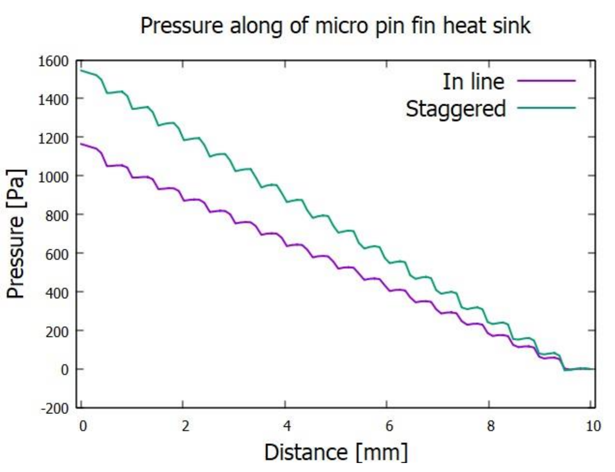
Graphic 4 shows the thermal resistance calculated with Equation 5 for all the cases studied, considering different Reynolds numbers. It can be seen that the case with the highest thermal resistance is Case 1, which corresponds to the in-line arrangement, and the case with the lowest thermal resistance is Case 2, which is the staggered arrangement. For the other cases, it is observed that the larger the diameter of the microfins in the second row, the lower the thermal resistance.



Graphic 4 Comparison of thermal resistance for the different cases analyzed
Source: Own elaboration

Another important parameter to analyse is the pressure necessary to move the cooling fluid inside the heat sink with micro fins. Graph 5 shows the fluid pressure along the heat sink, comparing the in-line arrangement and the stepped arrangement; the results show that the stepped arrangement requires a higher pressure to move the fluid inside the arrangement, but it is also the one with the lowest thermal resistance, as shown in Graphic 4.

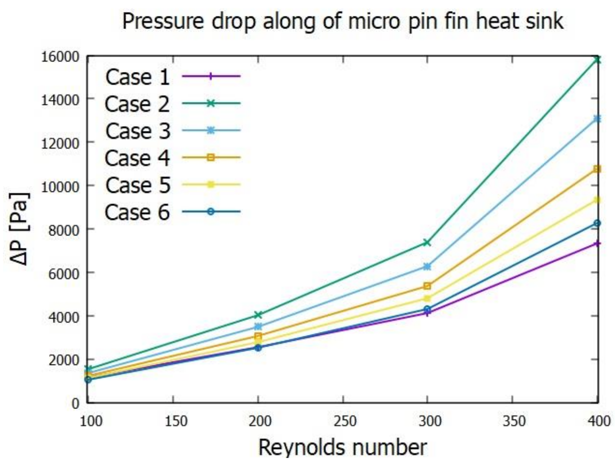


Graphic 5 Comparison of pressure along the micro finned heatsink with an in-line array and a staggered array
Source: Own elaboration

The following equation is used to calculate the pressure drop across the heatsink:

Where P_{ent} is the pressure at the inlet of the micro-finned heat sink and P_sal is the outlet pressure across the heatsink. The results of the pressure drop for the cases studied are reported in Graphic 6.

In Graphic 6, a comparison of the pressure drop across the heat sink is made for the different cases studied for different Reynolds numbers. As expected, the one with the highest pressure drop is the staggered arrangement, the one with the lowest drop is the in-line arrangement, and for the other cases, as the diameter of the second row of fins increases, the pressure also increases.



Graphic 6 Comparison of pressure drop along the heatsink
Source: Own elaboration

From the results of the pressure drop shown in Graphic 6, it can be seen that the pressure drop of Case 1 and Case 6 have very little difference, where Case 1 corresponds to the in-line arrangement and Case 6 to the stepped arrangement when using a ratio of Ø_or⁄(Ø_1=) 0.2, this result is relevant because with the same magnitude of pressure drop there are different thermal resistances, being lower in Case 6.

$$\Delta P = P_{ent} - P_{sal} \quad (8)$$

Conclusions

Numerical analysis of a heat sink with micro fins is carried out, the geometry of the micro fins is circular. The geometry of the heat sink is constructed, considering two types of arrangements for the micro fins, the in-line arrangement and the staggered arrangement, this type of arrangement is the one commonly used in cross-flow heat exchangers used in the petrochemical industry.

For the staggered arrangement it is considered to use a variant, the second row of micro fins will have a smaller diameter than the first row, using the ratio of ∅_or⁄∅_1.

The construction of the mesh is carried out and a mesh sensitivity analysis is performed to obtain the best mesh to be used in the numerical study.

The results show that the heat sink with an in-line micro-fin array maintains an average temperature of 299.56 K over the base of the heatsink, which indicates that it would keep the electronic chip working at allowable temperatures. When using the staggered array for the micro fins this average temperature is even lower, being 297.62 K.

The pressure drop results are reported for each of the cases analysed, from the results it can be concluded that the highest pressure drop occurs when using the stepped array in Case 2, and the lowest pressure drop occurs in the in-line array (Case 1) and in the stepped array with a ratio of ∅_or⁄(∅_1=) 0.2 (Case 6).

From here it can be concluded that the stepped arrangement is the one with the lowest thermal resistance, but it is also the arrangement with the highest pressure drop, so a balance must be found between thermal resistance and pressure drop, taking into account these two parameters it can be concluded that the geometric arrangement with the best thermal and hydraulic performance is the stepped arrangement of Case 6, which is the one with a ratio ∅_o⁄(∅_1=) 0. 2, this will have a lower thermal resistance compared to the in-line un arrangement and a pressure drop of the same magnitude as the in-line un arrangement.

Acknowledgements

The authors would like to thank the Polytechnic University of Juventino Rosas (UPJR) for the support provided for the development of the project.

Nomenclature

k	Thermal conductivity, (W/m-K)
c_p	Specific heat, (kJ/kg-K)
q''	Heat flux, (W/m2)
Rt	Thermal resistance, (K/W)
T	Temperature, (K)
ΔP	Pressure drop, (Pa)
S_T	Transverse micro-fin spacing, (mm)
S_L	Longitudinal spacing between micro fins (mm)
$\vec{V}$	Velocity vector
	Greek symbols
$\emptyset_o$	Largest diameter (mm)
$\emptyset_1$	Minor diameter (mm)
ρ	Density, (kg/m3)
μ	Dynamic viscosity, (kg/m-s)
f	Subscript
ent	Fluid
sal	Inlet

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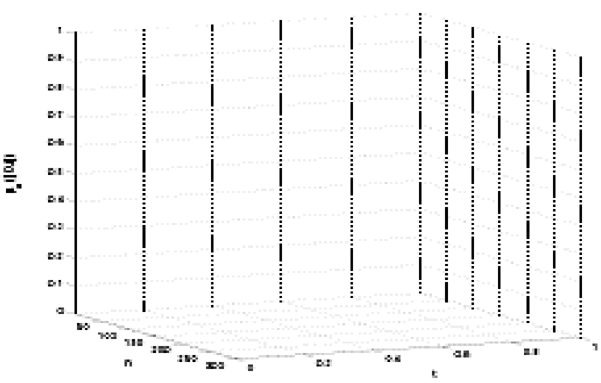

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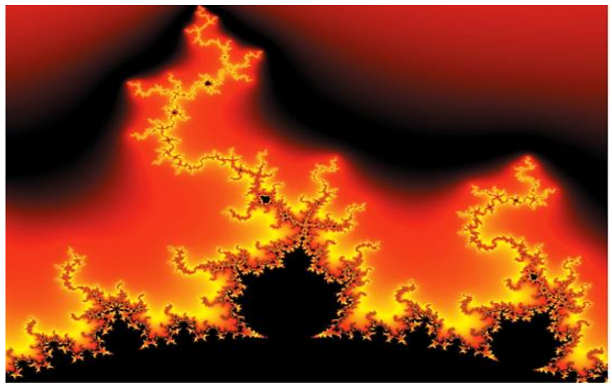

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