Study case: evaluation of pallets manufactured by structural foam with polietilene from analysis by the finite element method and mechanical tests

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Abstract. This document presents the implementation of the methodology for the evaluation of non-metallic materials, through the modeling, simulation and diagnosis of components manufactured by the high-density polyethylene injection method called structural foam, where a mixture is made between an inert gas and polyethylene of two origins: a part of recycled material and the other part of new material. This type of manufacturing is carried out for the shaping of stowage-type components, for the transport of containers of liquid substances. For the evaluation of the Stowage, a simulation was carried out from a commercial modeling software, Autodesk Inventor, based on the geometry, the mixture of materials, the attachment points and border parameters, the location and type of loads to simulate, and the different ways in which the loaded stowage would be used. After this, mechanical tests were carried out to determine the properties of the materials in their different mixtures and a feedback process of the finite element model was carried out, thus obtaining results with a minimum error factor, and thus issuing a diagnosis, focused on which material mixing ratio was the most suitable, based on the critical points of the stowage, its stress and deformations, and its safety factor. Finally, the existence of imperfections (bubbles), typical of the manufacturing process, which tend to have an incidence as concentrators of intrinsic efforts, and as critical points, is considered.

1. Introduction

The environmental impact generated by spills of the different chemical substances involved in the Colombian industrial sector, evidenced in sectors particularly such as hydrocarbons, which has led to the contamination of different water sources and ecosystems in general, has generated great concern to the population in general, depending on what should be the correct handling of these products, which, although they are essential for economic and commercial development, do not justify irresponsible practices in environmental matters.

In relation to the above, and extrapolating this condition to the other productive sectors, the national government has been implementing mechanisms to foresee, control and mitigate the impact of this type of products, through the obligatory nature of tools that allow to contain this type of chemicals before any eventuality that may arise, a condition that became an opportunity for the development and implementation of new technologies for companies such as Soliplast, Colombia; by virtue of this, Soliplast, Colombia, developed a product to meet the need of the national market in terms of the correct storage of lubricating oils, used oils, detergents, hazardous waste and, in general, chemical products of different characteristics, ensuring their containment and avoiding imminent risks. with the
implementation of anti-spill pallets (EAD, for its acronym in Spanish), based on innovative national manufacturing processes such as injection molding using the structural foam manufacturing technique, as well as production mostly with plastic recycled such as high-density polyethylene (HDPE) [1-5].

The objectives of this work evaluate the different material mixtures (recycled, new and additives), obtaining the best option for the fulfillment of the engineering requirements as well as the environment. On the other hand, evaluate the structural mechanical properties under static conditions in different case studies, using the finite element method (FEM) [6,7] applied by computer-aided design (CAD)/computer-aided engineering (CAE) tools [6], according to the physical model extrapolated from reality. Finally, evaluate the results of the manufacturing process from the defects evidenced in the current manufacturing, looking for the conditions for the application of the structural foam.

2. Experimental
The experimental development initially contemplated the product design parameters, that is, its use parameters that will guide the correlation of the real situation with the physical model, as well as with the CAD/CAE modeling process.

2.1. Product anti-spill pallets and manufacturing
The dimensional characteristics of the pallet contemplate a capacity to locate 4 barrel-type containers of up to 55 gallons of chemical products, which represents a minimum dam capacity of 208 gallons, manufactured in a material that is chemically compatible with multiple substances, such as high-density polyethylene, with maximum ventilation, which allows flexibility and safety for its transport, as well as the presence of a grid that allows the flow of the containers to the dike, as shown in Figure 1.

![Figure 1. Pallet EAD.](image)

For the manufacture of the pallet, a process called structural foam molding process is carried out, which consists of the injection of a plastic product mixed with an inert gas, under certain conditions of pressure, temperature, speed, and gas/plastic ratio. to some metal molds (male/female) of high weight, which enters through specially distributed nozzles, generating the final product.

2.2. Modeling and simulation
The modeling was carried out based on the fulfillment of the objectives of this work, obtaining the best performance of the material and the manufacturing process, achieving a minimum error rate in terms of the model extrapolated from reality to the CAD/CAE software, which allows, by applying the finite element method to static structural analysis, significant improvements or material optimization processes improving the cost/benefit ratio for the company.

2.2.1. Standard material. For the implementation of the model, initially, the reference parameters of the material to be evaluated are established, in this case, the high-density polyethylene [1,2], taking as information the default material loaded in Autodesk Inventor [6], and adjusting the properties according to one of the bases of data used by CAD/CAE type software such as MatWeb [7] or manufacturers in general, as shown in Table 1.
of specimens per test and are presented in relevant results are obtained, both for stresses and for critical deflections, which are averaged by pairs

\[ T_{	ext{Young's modulus}} = 72.50 - 174.05 \]

\[ T_{	ext{Poisson's ratio}} = 0.46 \]

\[ T_{	ext{Elongation}} = 12 \]

\[ T_{	ext{Tensile strength}} = 2.90 - 4.35 \]

2.2.2. Evaluation of the material and its variations. For the selection of the most suitable material and proportions, 3 scenarios were proposed, considering the different mixtures of high-density polyethylene, depending on the new material, the recycled material, and the different additives to be added that could give good results, in terms of mechanical properties such as ease or better results in terms of the manufacturing process.

2.2.3. Mixtures of materials and mechanical tests. Depending on the three types of material, the injection process is carried out maintaining the same parameters of material load and gas pressure, thus:from the resulting product samples are taken to carry out destructive tests to obtain mechanical properties and inspect in detail the manufacturing results, superficially evaluating the final product, specifically in ribs, corners, shaping and filling of the mold in different thicknesses.

Subsequently, samples are taken and specimens are machined to proceed to carry out the different mechanical characterization tests by means of tension tests and bending tests, as referenced in the American Society of Testing Materials (ASTM) standards, ASTM D638 [8] and ASTM D790 [9], as presented in Avalle [10], respectively; These tests will allow to evaluate which is the material or the mixture of materials that presents a better mechanical performance for the intended application and, additionally, it will allow to adjust the standard material loaded in the CAD/CAE tool, adjusting the results to parameters closer to reality, taking as a guide the process carried out by Chen [11] in his publication.

For the execution of the tests, 5 test pieces were manufactured per test according to the dimensions established by the different standards, however, due to the manufacturing process, 3 of the 5 test pieces presented discontinuities or defects that affected the performance of the test and were rejected by the requirements of its execution, as established by Heydari [12] in his publication, where the presence of these defects influences the distribution of stresses; Figure 2 show the stress/strain curves obtained of tension tests.

From the interpretation of the graphs of the tensile tests, shown in Figure 2, the most relevant results are obtained, both for stresses and for critical deformations, which are averaged by pairs of specimens per test and are presented in Table 2; for the execution of the tests 3 materials are evaluated; virgin high-density polyethylene (New HDPE); a mix between recycled and virgin polyethylene (Mix A: recycled+new HDPE), and a mix between recycled polyethylene, virgin, and additives (Mix B: recycled+new HDPE+ad).

### Table 1. Mechanical and chemical properties according to literature [1] for the HDPE.

| Standard mechanical properties | Chemical compatibility: Good-acceptable |
|-------------------------------|----------------------------------------|
| Elastic modulus - E (ksi)     | 145.04                                 |
| Coefficient of friction       | 0.29                                   |
| Young’s modulus (ksi)         | 72.50 – 174.05                         |
| Poisson’s ratio               | 0.46                                   |
| Elongation (%)                | 12                                     |
| Tensile strength (ksi)        | 2.90 – 4.35                            |

| Chemical compatibility: Good-acceptable |
|----------------------------------------|
| Concentrated acids                    |
| Ketons                                 |
| Dilute acids                           |
| Alcohols                               |
| Grease and oils                        |
| Aromatic hydrocarbons                 |
| Halogen’s hydrocarbons                |

### Table 2. Results of the mechanical characterization tension tests.

| Tensile test | New HDPE (100%) | Average | Mix A | Average | Mix B | Average |
|--------------|------------------|---------|-------|---------|-------|---------|
| Elongation (%)| 4.28             | 5.62    | 4.95  | 2.50    | 2.20  | 2.35    |
| Yield stress (ksi) | 0.71      | 0.83    | 0.77  | 0.59    | 0.47  | 0.53    |
| Tensile stress (ksi) | 1.29     | 1.51    | 1.41  | 1.09    | 0.89  | 0.99    |
| Ultimate stress (ksi) | 0.78      | 0.93    | 0.85  | 0.66    | 0.54  | 0.60    |

In the same way, from the interpretation of the graphs obtained in the 3-point bending test; the most relevant results are obtained, both for stresses and for critical deflections, which are averaged by pairs of specimens per test and are presented in Table 3.
Table 3. Results of the mechanical characterization bending tests.

| Mechanical tests | New HDPE (100%) | Average | Mix A | Mix B | Average |
|------------------|-----------------|---------|-------|-------|---------|
| Flexural stress (ksi) | 3.04 | 3.02 | 3.03 | 1.37 | 1.17 | 1.27 | 3.42 | 3.51 | 3.37 |
| Flexural strength (%) | 11.78 | 13.01 | 12.40 | 10.09 | 10.53 | 10.31 | 16.57 | 16.91 | 16.74 |
| Modulus of elasticity (ksi) | 85.71 | 96.71 | 91.21 | 42.04 | 36.81 | 39.43 | 80.38 | 84.59 | 82.48 |

From the results previously presented in Tables 2 and Table 3, the most relevant of each material is consolidated and it is observed that, in terms of the individual mechanical properties of each material, Mix B is the one that presents the results closest to the reference of the literature [1,2].

Table 4 presents the results obtained in comparison with reference [1], where a relative error is observed with respect to the maximum stress of 2.75%, with respect to the elastic limit of 59.66% and with respect to deformation at break above requirement. Regarding the modulus of elasticity, the relative error is 43.13%; this mixture being the one with the best performance.

Table 4. Consolidated results of mechanical characterization tests.

| Mechanical tests | Tensile stress (ksi) | Yield limit (ksi) | Elongation (%) | Flexural stress (ksi) | Deflection (%) | Elasticity modulus (ksi) |
|------------------|----------------------|------------------|----------------|----------------------|----------------|------------------------|
| Reference [1]    | 2.18 – 5.80          | 2.90 – 5.80      | 12             | -                    | -              | 145.04                 |
| New HDPE         | 1.41                 | 0.77             | 4.95           | 3.03                 | 12.40          | 91.21                  |
| Mix A            | 0.99                 | 0.53             | 2.35           | 1.27                 | 10.31          | 39.43                  |
| Mix B            | 2.12                 | 1.17             | 12.27          | 3.37                 | 16.74          | 82.48                  |
2.2.4. **Computer-aided design modeling using Inventor.** The design process carried out by Soliplast S.A. based on compliance with the product requirements is taken as a basis (see Figure 3), verifying, and simplifying the geometries, taking as a basis that convergence errors do not occur in the simulation processes, motivated by empty geometries or errors in areas of application of forces or restraint.

![Figure 3. 3D CAD model in Autodesk Inventor [2].](image)

2.2.5. **Implementation of the finite element method and stress cases.** For the evaluation by FEM simulation, 2 load cases are considered that recreate possible ways of using the stowage such as lifting by forklifts and hoisting, and a third case is considered for a theoretical load in a comparative way, such as is the 3-point bending, as presented in Figure 4.

![HYPOTHETICAL CASE FOR COMPARISON](image)

![Figure 4. Load study cases; (a) case 1: forklift; (b) case 2: lifting; (c) case 3: 3-point bending.](image)

3. **Results and discussion**

The different results obtained based on what is evidenced by the FEM are presented, and their correlation with the diagnosis and the best results obtained, and finally the correlation of the real material and the manufacturing defects is included.

3.1. **Evaluation of simulation results using finite element method**

The simulation by FEM was carried out following the sequence of activities shown in the figure below, where initially the physical model is proposed from the real situation, where the respective load/effort parameters are considered, the type of support to be used, and the restrictions and/or assumptions applicable to each case; The next step contemplates the simplification of the CAD model to a composition of force vectors and the structures to be analyzed; Subsequently, the discretization is made, generating the infinitesimal elements with the different sizes and refinements that the model requires, and later the corresponding structural static simulation is generated, evaluating the parameters of the Figure 5.
From this CAD/CAE simulation process, it is possible to obtain the results for each case and for each material mix, where two conditions stand out; in the first place, it is observed that although case 1, presented in Figure 5, is the most common in conventional life, it is the condition with the lowest evaluated load; on the other hand, case 3 shows the higher load requirement, which corroborates that mixture B presents the best properties to withstand stresses, as shown in Table 5, taking into account that the simulation is carried out under ideal conditions of the material (no manufacturing defects).

Table 5. Results of the FEM simulations.

| Case studies by material | Case 1 | | | Case 2 | | | Case 3 | | |
|--------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
|                          | New HDPE | Mix A  | Mix B  | New HDPE | Mix A  | Mix B  | New HDPE | Mix A  | Mix B  |
| Tensile stress (ksi)     | 0.319   |        |        | 0.506   |        |        | 0.529   |        |        |
| Displacements maximum (in)| 0.0031  |        |        | 0.0337  |        |        | 0.0410  |        |        |
| Safety factor            | 2.42    | 1.66   | 3.67   | 1.52    | 1.04   | 2.31   | 1.46    | 1.00   | 2.21   |

3.2. Real material and manufacturing defects

In the analysis of the geometries of defects presented in the foaming process, the presence of morphologies such as: discontinuous areas (jumps in the material) that may refer to lack of material, bubbles due to the non-homogeneity of the product material could be evidenced temperature or lack of adhesion between materials, as well as drains that are due to the compression factor of the material at different temperatures, lack of material, or inadequate design of injection points, for which, the provisions could be taken into account by Chen [13], where a control method is established, based on a pressure/temperature control system.
According to the results of the failures and discontinuities evidenced in the injection, presented in Figure 6, a comparison is made with that presented in the publication of Tromm [14], where they relate similar defects, and the variables influencing the control of the size and density of the detected defects. Specifically, the authors establish that these defects will depend on the injection pressure of the plastic, the injection time, as well as the gas injection pressure (Zhao [15]), the amount of material injected, the temperature of the mold and the number of points. injection you have. In his publication, Barbosa [16] and Lee [17], establishes the relationship between geometries and injection and the different parameters through simulation that support the process carried out and the way to obtain better results.

4. Conclusions
The results obtained established that Mix B material presented the more suitable mechanical properties for the specific application. Three evaluation cases were established according to the possible forms of use and operation of the product, where the most critical condition corresponds to the 3-point bending. Moreover, the product was evaluated using the CAD/CAE Inventor tool, and the tensile and bending tests, taking the results as the basis of the loaded materials for its simulation. The base of the product is identified as a critical point to be reinforced by means of geometries and/or material.

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