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Feasibility of utilization of recycled HDPE in manhole covers for urban traffic areas and industrial zones

M. Suffo [a,*], M. Brey [b], J.P. Orellana [a], J.L. García-Morales [b]

[a] Department of Mechanical Engineering and Industrial Design, High Engineering School, Universidad de Cádiz, Campus Río San Pedro S/n 11510, Puerto Real, Cádiz, Spain
[b] Department of Environmental Technologies, Faculty of Marine and Environmental Sciences, IVAGRO-Wine and Agrifood Research Institute, University of Cadiz, Spain

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ABSTRACT

The consumption of plastic raw materials has been exponentially growing throughout the world in the last decade and so has, in the same proportion, their associated waste. Recycling through the mechanical treatment of the heavy fraction of these plastics is the most economic and the safest alternative to use this waste and to recirculate it for reuse within the same industry or for other related industries located near the place where the waste is generated. In this paper, a study of characterization and post-processing of recycled high density polyethylene received by a hazardous waste manager in southern Spain is presented, an area in which containers, Intermediate Bulk Containers, and drums, originally used for oil products from refineries and petrochemical industries nearby, are employed. These high density polyethylene materials are validated to meet the requirements of the harmonized standards to be used as self-supply in the production of manhole covers. EN 124–6:2015 standard allows the use of plastic materials such as PE or PP, even using material externally reprocessed, such as material derived from thermoplastic products that have not been previously used as lids or manhole covers. Class A-15 and B-125 of the standard are oriented for the construction of these types of elements to cover or close in certain urban spaces such as pedestrian areas, parking areas or multi-story car parks for vehicles. The study shows that the recycled material fully complies with the density; it keeps unalterable during fire test after application of the coating, there are no adverse effects on artificial ageing; the decrease of the average value of the tensile impact strength by 21.84%; and achieves 6 mm of maximum deflection against the test load Fp (45.3 MPa). Therefore, it can be considered a valid scenario for the effective use of solid plastic waste in products that make up part of the urban or industrial areas, as an example of complete circularity material and offers a valid alternative to the end-of-waste condition.

List of abbreviations / nomenclature

D	Density, kg/m^3
σ_m	Ultimate strength, MPa
σ_y	Tensile stress at yield, MPa
DSC	Differential scanning calorimetry
E_n	Absorbed impact energy
E_s	Impact energy absorbed by the material in the tensile impact test
EDX	Energy-dispersive X-ray spectroscopy
E_t	Young's modulus (determined in tensile test), MPa
ε_m	Strain at strength, MPa
ε_{tb}	Strain at break, MPa
EoW	End of Waste
HDPE	High density polyethylene
IBCs	Intermediate Bulk Containers
rHDPE	Recycled high density polyethylene
$rHDPE_o$	Recycled high density polyethylene of IBCs with industrial oil content
$rHDPE_n$	Recycled high density polyethylene of IBCs without industrial oil content final composite blend (BrHDPE)
BrHDPE	Blended and recycled high density polyethylene; 50% $rHDPE_o$ and 50% $rHDPE_n$ mix
l	Length, mm
m	Mass, g

* Corresponding author.
E-mail address: miguel.suffo@uca.es (M. Suffo).

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SEM	Scanning Electron Microscopy
t	Time, min
T	Temperature, ºC
T_m	Melting temperature, ºC
ΔH	Enthalpy rate, J/g
ε	Strain, %
ε_b	Strain at break, %
σ_{VM}	Von-Mises Stress, MPa
σ_b	Stress at break, %

1. Introduction

According to Plastic-Europe (2023), in 2021 the world production of plastics was of 390 million tons (57.2 million tons in Europe). Also, in 2020, 29.5 million tons of plastics were collected in Europe as waste: of these, 34.49% was collected for recycling, 42.25% incinerated, and 23.25% landfilled. It has been determined that the production of virgin plastic generated the equivalent of 1.78 Gt of CO_2 during 2015, with this amount estimated to rise to 6.5 Gt by the year 2050 (GlobalCarbon, 2021; Geyer et al., 2017). K. Ragaert et al. (2017), reported a 50% reduction in CO_2 emissions by recycling plastic for the creation of new products, and a 66.6% reduction in energy consumption compared to the production of virgin plastic. However, the possibilities of plastic recycling are remarkably underdeveloped, with 91% of produced plastic not being recycled (Meys et al., 2020). Despite the alternative presented by the mechanical recycling of Plastic Solid Waste (PSW), it is still not widely adopted (Gu et al., 2017). Waste management systems still do not have a recovery/utilization system that allows for subsequent recycling into raw materials or products to be reused within their own industries, particularly in developing countries (Ragaert et al., 2017). The uncertainty about the behaviour of this recycled plastic has not contributed to its widespread use, so the European Union in 2014, through the Joint Research Center (JRC), made a report on the necessary technical requirements associated with the end of waste (EoW) status for plastic waste (Villanueva and Eder, 2014). The implementation of EoW criteria serves a dual purpose: preventing ambiguity in waste classification and offering clarity on when recovered waste no longer retains its waste status. By establishing transparent EoW criteria, recycling is supported with legal certainty, promoting fair competition between recycled materials and virgin material production. Spain has been the first European country to enact legislation that establishes end-of-waste criteria specifically for plastic waste derived from mechanical treatment (Order TED/646, 2023). However, it is crucial to acknowledge that this legislation focuses exclusively on thermoplastics, such as HDPE, and does not encompass thermoset plastics.

All this development is framed within all EU circular economy policies since 2015 (Zheng and Suh, 2019a,b). In a specific 2019 study (Crippa et al., 2019), emphasized the opportunities presented by the implementation of a circular economy for plastics. This vision entails transforming recovered plastic waste into new, fully reusable products with a Material Circularity Index (MCI) of approximately 1 (Corona et al., 2022). A good example of this is the recycling of HDPE containers, drums, and IBCs to be used for the production of new products, such as containers, pipes, toys, or garden furniture, among others. In addition to this, the recovery of this plastic waste can also create employment and business opportunities in the circular economy sector.

Once they arrive at the treatment plant, they are washed and crushed while maintaining all the physical and chemical properties prior to the first processing. For this reason, they can be used as raw materials for other types of elements, such as those used in public or private urban equipment (ScottBaderCompany, 2015; Suffo et al., 2023).

Nowadays, a variety of mechanically recycled plastics, such as HDPE, can be used in different sectors (Crippa et al., 2019). These recycled HDPE materials are in great demand in construction (Nyika and Dinka, 2022; da Silva et al., 2021), packaging (Crippa et al., 2019) and other sectors such as furniture and consumer goods sectors (Villanueva and Eder, 2014; Singh et al., 2017; Lamba et al., 2022).

There are many applications that need encasements or manhole covers in points of access such as manholes, drains, and inspection chambers, which are subjected to pedestrian and/or vehicle traffic. Most of the manhole covers found on the road, sidewalks, or other spaces such as bike lanes or pedestrian areas are usually made of metal (ductile iron), and most of them are oversized considering the actual requirements that these elements must meet (El Haggar and El Hatow, 2009). Additionally, there are elements covering up confined spaces containing vapours that are corrosive to metal, and this implies their frequent replacement, with a high economic cost for companies. Metallic materials respond with contractions, expansions, and corrosion associated with climatic factors that cause defects in the pavement. Currently, conventional cast iron covers are being replaced with HDPE manhole covers in underground 5G signal transmitters (Fibrelite, 2020). This is because conventional manhole covers, being made of cast iron, reflect the signal, attenuating its intensity. However, manhole covers made of plastic materials have a lower coefficient of absorption, making them ideal for this purpose. The downside of thermoplastic RSPs is that once they reach the treatment plant, it is almost impossible to maintain their traceability without mixing them with each other, varying their physical-mechanical properties and turning them into a "blend" of both, with new properties (El Haggar and El Hatow, 2009). References to the use of rPE in the agriculture sector, such as for agricultural seedling trays and horticultural applications with a maximum recycling content of 50%, are common (Gu et al., 2017), but replacement of products with 100% rPE material is not common. The UNE EN 124–6:2015 (UNE-EN, 2015; Falk, 2000; El Haggar and El Hatow, 2009) standard includes the use of plastic materials such as PE or PP for the construction of these types of elements to cover or close in certain urban spaces such as pedestrian areas, parking areas or multi-story car parks for vehicles (Class B-125). This standard contemplates the possibility of using material externally reprocessed, such as material derived from thermoplastic products that have not been previously used as lids or manhole covers.

Given that the most important concern is the unpredictability of their mechanical properties (modulus of elasticity, tensile strength, and ductility) (Sawalha and El-Hamouz, 2010), the objective of this research work is to study the feasibility of using fully recycled plastic materials as raw materials to design and manufacture these types of elements that are so common in urban spaces. For this purpose, the recycled materials must meet a series of requirements, thus their mechanical properties will be evaluated through tensile impact tests, artificial aging through xenon/UV arc, deformation under load tests, as well as determining residual deflection through numerical simulation by FEM, and the mechanical properties of BrHDPE will be determined through tensile testing. Their thermal properties will also need to be evaluated with a fire resistance test.

2. Material and methods

Fig. 1 summarizes the methodology followed in the research. The RSP in their initial form are shown in blue and with continuous lines, the resulting BrHDPE in yellow and dashed lines and, finally, the processes in orange.

2.1. Materials

Because both recycled high density polyethylene of IBCs with and without industrial oil content ($rHDPE_o$ and $rHDPE_n$) are generated in

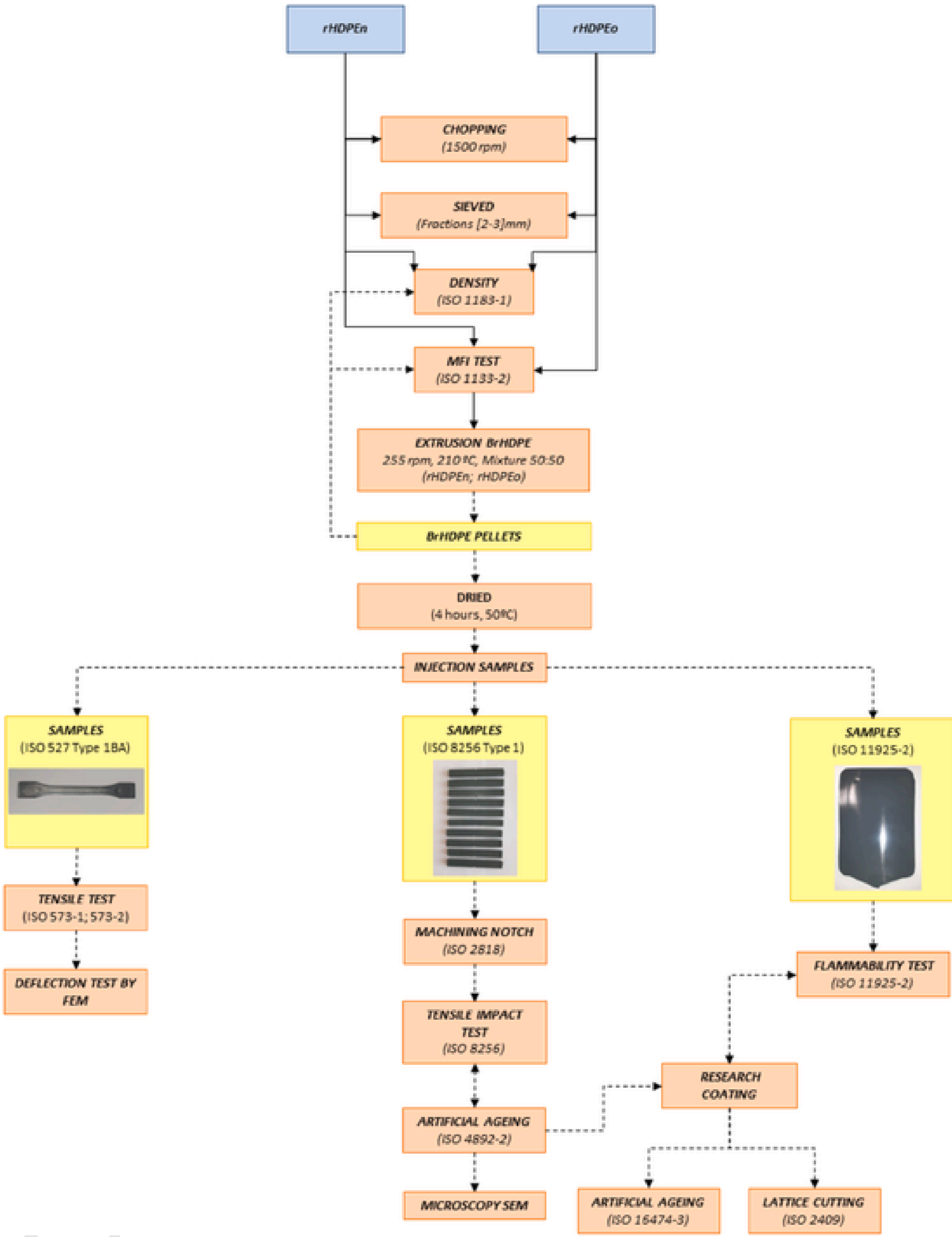

Fig. 1. Flow chart of the research methodology.

equal amounts, the resulting blend used is based on the mixture of two types of HDPE (Table 1).

The origin of these materials comes from containers, drums, and IBCs, one of which will have contained industrial oils. To differentiate them, the material that has contained oil will be referred to as rHDPEo and the one that has not as rHDPEn. As it can be seen in Fig. 2a), due to the processing in the treatment plant, contamination of these initial materials with other low-density polyethylene (LDPE, LLDPE) is inevitable, which is why it is necessary to consider this heterogeneity in the characterization.

The thermoplastics have been provided by the waste management company Verinsur, the main waste manager in the province of Cadiz (in the south of Spain). The origin of the final composite blend (BrHDPE) is obtained through a grinding process for the material fractions in a SM 300 mill at a speed of 1500 rpm. The resulting grind is then sieved using a Retsch SA 200 sifter with a 2–3 mm sieve (Tesfaw et al., 2022).

Table 1
Characteristics of blend BrHDPE.

Morphology	Fraction of drums of 2–4 cm.
Genesis	Grinding and milling process of the drums with subsequent extrusion
Chemical composition	50% $rHDPE_n$ 50% $rHDPE_o$
Volume	Estimation of 540 tons per year (45 tons per month)

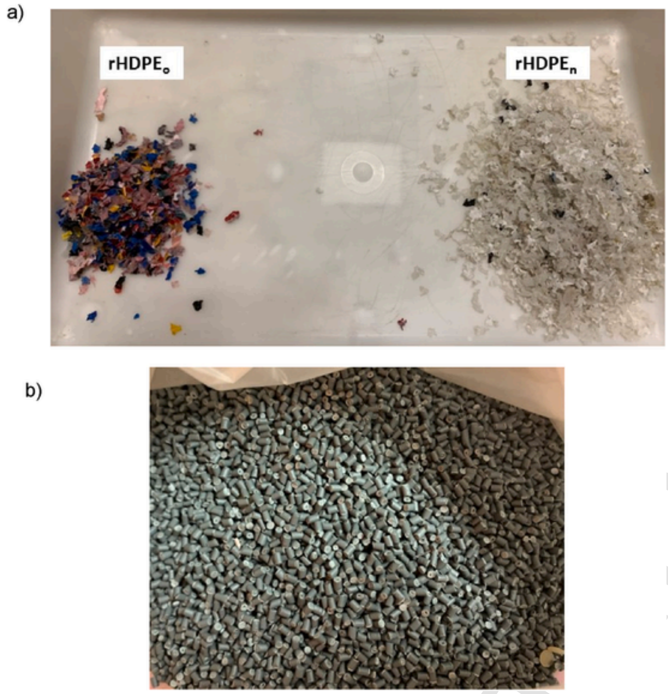

Fig. 2. *Physical appearance of: a)* rHDPE granules before mixing; b) *BrHDPE formed with a* 3-mm *size.*

The pellets are subjected to a drying process at 100 °C for 24 h to remove any moisture present after the cooling process. Using a two-hopper extruder model, The Balance Movacolor, and the result of the previous process, an extrusion process is carried out to form the BrHDPE. This process was carried out at a speed of 255 rpm and a temperature of 210 °C (Moya-Muriana et al., 2020). After the extrusion process, the material comes out in the form of continuous thread, which is cooled and then chopped into granules (see Fig. 2b).

2.2. *Methodology*

The approach followed in this study is summarized in Fig. 1. The material characterization methods described below have been carried out in accordance with the requirements set forth in the UNE-EN 124–1 and UNE-EN 124-6 standards.

2.2.1. *Density and fluidity*

The densities of rHDPEn and rHDPEo were determined, as well as their blend (BrHDPE), using the immersion method (UNE-EN ISO 1183–1). These tests were performed using distilled water as the immersion liquid. Similarly, the materials were subjected to the flow rate test (UNE-EN ISO 1133–2), which, by applying Method A (Measurement of Mass), allows for the individual determination of the MFR (Melt Flow Rate) of each material and their blend. This test was carried out at a temperature of 190 °C, with a preheating time of 300 s and a nominal load of 5 kg. The time between cuts was 120 s. The tests were conducted under ambient conditions of 23 °C and 50% relative humidity.

2.2.2. *Impact and tensile strength and microscopical analysis*

For the execution of the tensile impact test, the methodology proposed in the UNE-EN ISO 3127 standard was followed, which aims to determine the impact energy absorbed (E_s) by the material. For this, type 1 BrHDPE test specimens were injected according to the UNE-EN_ISO 8256 standard (Method A), with dimensions of 80 × 10 × 6 mm, and were tested at a room temperature of 23 °C, on a Ceast Resil Impactor Junior machine. These test specimens were injected using an Engel 28 TN machine, in which the material injection temperature is 200 °C at a maximum pressure of 170 bars and has a cooling time of 20 s (Wongpanit et al., 2014). These test specimens were machined with a double notch according to the UNE-EN ISO 2818 standard.

The same test was applied to two series of test specimens, a first series without applying treatment and a second series having previously undergone an artificial aging test according to the UNE-EN-ISO 4892-2 standard, as described below in section C. It is intended to verify that the absorbed impact energy (E_n) of the test specimens with Artificial Aging (AA) does not decrease to less than 50% of the value obtained for the test specimens that have not been subjected to AA.

In the tensile impact test, a hammer with a nominal energy of 25J, a reduced mass of 3.655 kg, and a length of 0.374 m was used. The test specimens were fixed to the test stand using a steel clamp of 0.06 kg and with a free length between grips of 30 mm, an angle of the pendulum of 50°, a test speed of 1.62 m/s, and a nominal impact energy of 4.79 J.

Finally, to check the type of fracture suffered, the fractured test specimens were studied by scanning electron microscopy (SEM), using a Thermofisher Scios 2 microscope with a double beam at an acceleration voltage of 10 kV. To visualize the fracture area in cross-section, the sample was tilted 52 °C. The microscopic study was applied to the two series of test specimens.

2.2.3. *UV stability, coating and grid-cut testing*

As indicated in section B, in order to guarantee the resistance to degradation of BrHDPE when exposed to the outdoors, an artificial aging test was performed according to the UNE-EN ISO 4892-2 standard, method A. The geometry of the test specimens used were of type 1 under the UNE-EN ISO 8256 standard.

To study the recycled thermoplastic material's behaviour under external weather effects, an artificial aging chamber, model Q-SUN Xe-3-HSE, with xenon arc lamps, was used for the test, with a total duration of 500 h. To check the level of colour variation of the samples, the UNE-EN 20105-A02 standard requires not to exceed stage 3 of the grey scale. To determine this colour change, a spectrophotometer model XRITE Colour i7 was used, and the standardized CIELAB colour space was used as control parameters for colour coordinates.

To improve the colour change, different coatings were tested on BrHDPE. With this, it was expected to overcome the slight drop below the established value on the grayscale in the EA test. A layer of paint that guarantees the coating's resistance to UV rays was applied under environmental conditions of 25–27 °C and with a relative humidity of between 50 and 60%. To select the best painting scheme, two phases are established. In the first phase 3 schemes are tested, Barnicoat 400E, Novolack and Novoacrilic to the "Eurotex TCH" manufacturer (Eurotex, 2023), on a series of small specimens of 78 × 10 mm. They underwent prior cleaning with acetone to remove grease and dirt and, additionally, these schemes will be tested on a series of tubes, some having been previously sanded down and the others with their surfaces unaltered. The coatings were tested with a repeatability of n = 3. In the second phase, the final schemes are tested on two large specimens of 250 × 90 mm with the following coatings.

- Barnicoat 400E: Sand with 180 grit + clean with xylene + primer of epoxy ester solvent-based nature + sand with 240 grit + 3 coats of aliphatic bicomponent polyurethane

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- Novolack: Sand with 180 grit + clean with 160–180 naphtha + primer of epoxy ester solvent-based nature + sand with 240 grit + enamel of alkyd nature.

In both cases, a chemical attack was carried out on the substrate through the cleaning process with xylene or 160–180 naphtha. These tests were conducted with a repeatability of n = 2.

To ensure adhesion of the coating to the thermoplastic material, a cross-cut test based on the UNE-EN ISO 2409 standard was applied. For this, once the coating is applied on a series of flat specimens without deformations, 6 perpendicular incisions are made between them, 3 to 3. These incisions are made with a V-shaped blade at 30°, spaced evenly at 3 mm. This test was applied to the comparative schemes and different substrate preparation processes to select the most stable adhesion. After the test, the results are classified with Table 1 of the UNE-EN ISO 2409 standard based on grades 0 to 5, with 0 being optimal.

To exclusively check the durability of the coatings tested against environmental conditions, a new climatic test was performed according to the UNE-EN ISO 16474-3 standard, method A. This test was carried out in an artificial aging chamber, model QUV Accelerated Weathering Tester with UVA-340 lamps, with an exposure time of 1000 h.

2.2.4. ***Reaction to fire*** *(Fire_Safety_Handbook, 2020)*

In order to determine the possible contribution of BrHDPE to a fire, the UNE-EN ISO 13501-1 standard establishes a classification of the material according to its response when subjected to a flammability test, according to the EN ISO 11925-2 standard. The flammability test consists of applying a direct flame to the sample to be tested, in this case it was applied at the centre of the width of the lower edge of the test sample, 1.5 mm behind the surface, as well as on the surface of the material itself. The flame application time was 15 s at an air speed of 0.7 m/s, and the flame application distance from the surfaces being studied was 20 mm. The test was performed in triplicate (n = 3). This test was repeated under the same conditions to verify that the applied coating resolves the slight decrease in EA and does not affect the obtained result.

2.2.5. Tensile test and numerical simulation of maximum deflection obtained by FEM

Before designing the final mould for the injection of the components (cover and frame), a check was carried out on the maximum directional deformation of the manhole cover when subject to an externally distributed load across its entire surface. According to the UNE-EN-ISO 124-6 standard, a load of value 2/3 (125,000 N) must be applied to Class B125 covers, i.e. P = 83,334 N, and the residual deflection must not exceed 6 mm with a CP = 600 mm, with the frame remaining fixed. To select the thickness of the manhole cover, simulations were performed by varying this parameter up to the point that the required limit was not exceeded, using a geometric configuration based on the dimensions shown in Fig. 3. Ansys mechanical APDL (steady structural) was used to perform simulations with different test thicknesses. A tetrahedral mesh composed of elements of a 2.3-mm size, with a total of 1,121,882 elements, was used. The ASME grid convergence index (GCI) method (Yershov and Yakovlev, 2021), was applied by varying the element size between the ranges of value (2.1–2.3 mm) and (2.3–2.5). A maximum allowable error criteria of 5% in GCI was decided upon. The ranges revealed an approximate average error of less than 1%.

In order to carry out the simulation, it was necessary to determine some basic mechanical properties of the material: Young's modulus in tension (E_t), tensile stress at yield (σ_y), and ultimate tensile stress (σ_m). For this purpose, a tensile test was carried out by injecting a series of BrHDPE material specimens, type 1BA following the ISO 527–2:2012 standard. The test was performed at a speed of 1 mm/min using a Tinius Olsen H10KS Universal Testing Machine, following the UNE-EN ISO 573–1 and UNE-EN ISO 573-2 standards to address the tensile strength mechanical properties of the material. The results obtained have been introduced as parameters of the new material created in the Ansys Mechanical APDL library for later use in simulations.

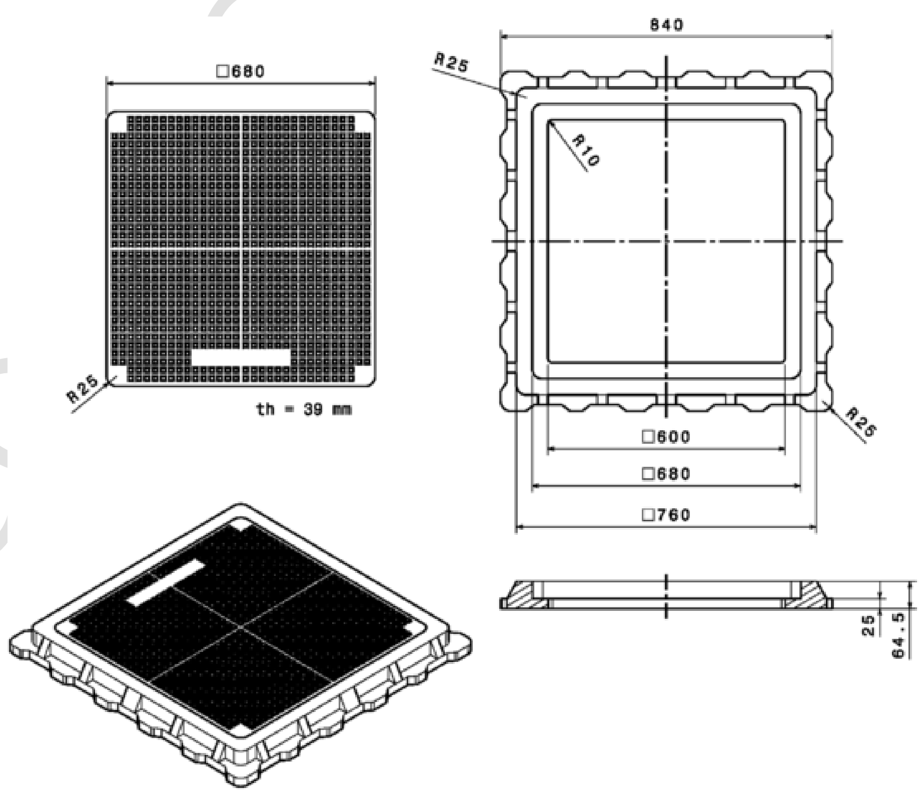

Fig. 3. The 3D Models, including an isometric view and basic dimensions.

3. Results and discussion

3.1. Density and fluidity

As can be seen in Fig. 4a, the values resulting from the fluidity tests are similar to those obtained in other studies in which a Melt Flow Index of approximately 0.9 g/10 min is observed, (Wu and Wang, 2019; Techawinyutham et al., 2021). Nonetheless, although the value of this parameter decreases by 47,7% compared to the study previously referred to, this phenomenon is common in plastic materials, both recycled and non-recycled, having undergone thermal cycling (Suffo et al., 2020). The MFI value of the BrHDPE may be due to the material used in the experiment being mainly made of $rHDPE_n$. In order to determine the influence of each of the rHDPE in the blend, it would be necessary to establish a strategical series of experiments segmenting according to the % of the blends. The thermal cycles along with the mobility of polymer chains, resulting from the transformation during the extrusion process, influence the crystallization kinetics to finally obtain mechanical and rheological properties similar to the ones of virgin HDPE (Mnif and Elleuch, 2015; Gaduan et al., 2023).

On the other hand, as shown in Fig. 4b, the density values of rHDPEo and rHDPEn are similar to the standard values of recycled HDPE (0.92) (Badache et al., 2018). Likewise, the density obtained for BrHDPE is similar to the standard values of Virgin HDPE (0.97) (Tian et al., 2021). Although density values are especially similar, the slight increase shown in BrHDPE is due to the process of compression suffered by the material in the screw of the extruder. This phenomenon was previously described by (Dorigato, 2021).

3.2. Impact resistance and microscopical analysis

In this section, two different stages are distinguished. First, the test was performed for a series of 8 specimens which were not subject to EA. The graphs included in Fig. 5b represent the material deformation curves and the tensile impact strengths achieved. BrHDPE presents valid results compared to the 15 MPa achieved in studies for PVC and PE, with an application speed of 1 m/s (Visser et al., 2013); furthermore, the strength values achieved are similar to those in the study (Candau et al., 2021), where a blend of PLA/GTRc ranges between 20/55 MPa. The results obtained in the same test applied to aged specimens are shown in Fig. 5a. These results present a decrease of the average value of the tensile impact strength by 21.84%, a result that validates the material for the intended purpose as it does not exceed 50%.

Fig. 5(c and d) show images taken at ×25, ×25, respectively, taking into account the morphology of the material fracture analysed through a SEM microscope. According to the type of footprint presented, in Fig. 5c, it is possible to determine that the material suffers a typical compression from tension, seen on the upper and lower convex surfaces. The breakage is observed to have taken place along a more or less straight vertical line. In Fig. 5d, it is verified that the break has been clean and that there are no holes or other imperfections. These are the fractures corresponding to the aged specimens. The analysis was carried out in the same way as in Chen et al. (2019) and Liu et al. (2021). This change has been produced due to a slight alteration in the material properties after exposure to EA, which is not worrying given the excellent results of the impact tensile tests.

3.3. UV stability, coating and grid-cut testing

It is a known effect that occurs in some thermoplastics, such as HDPE, that when exposed to artificial aging through UV application, their physical properties are affected, due to a process of photo-oxidation (Yildirim et al., 2022). The result of the climatic test shows a slight change in colour on the grayscale, which means an excess with regard to the threshold required by the standard. This implies the application of a coating that protects the material from that colour change. After conducting the first test, it was observed that the adhesion of the primer is limited (lower line of Fig. 6a, test tubes not previously sanded), therefore, the Barnicoat 400E scheme causes the coating to peel off more easily due to its hardness. However, the Novolack scheme behaves more resiliently, this can be observed in the upper row of Fig. 6a. These show greater adherence in the tested schemes compared to the lower ones, where the surfaces were not sanded.

In the second test, as shown in Fig. 6b, the coatings based on Barnicoat 400E and Novolack applied on large test tubes, with prior sanding, obtained a result of 0 on a scale from 0 to 5, 0 being the optimal result according to ISO 2409.

As can be observed on the surface of the large test tubes, the cross-cut test makes the traces of the blades visible, with no discernible detachment to the naked eye.

3.4. Reaction to fire

The flammability test had to be performed twice, the first to test the reaction to fire of BrHDPE and the second to test the same material with the applied coating. In neither case did the material detachment or the ignition of the filter paper placed at the bottom occur and, therefore, the addition of fire retardants or other materials was not necessary. Since particle ignition did not occur and flame propagation did not exceed 150 mm in height, the material obtained classification E. The results obtained in the tests were similar to those of references where the same test was performed on polystyrene plates with 2.5% SF-201 fire retardant compound in their composition (Mountassir et al., 2021a,b). Furthermore, in 2002, Reynoso et al. (2021) conducted the same test on a composite with a HDPE matrix and reinforced it with wood fibres, and, likewise, obtained satisfactory results. In this case, a flame propagation rate of less than 150 mm/min was also determined.

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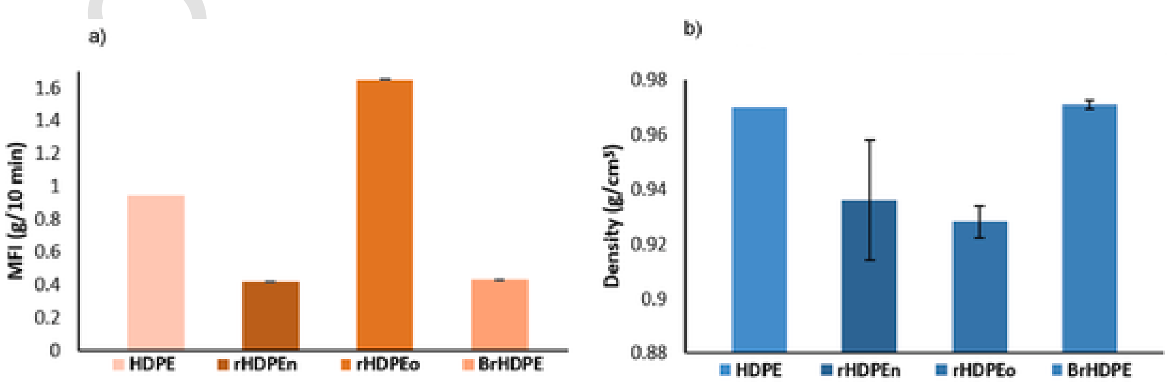

Fig. 4. Test results of: a) fluidity index and; b) density.

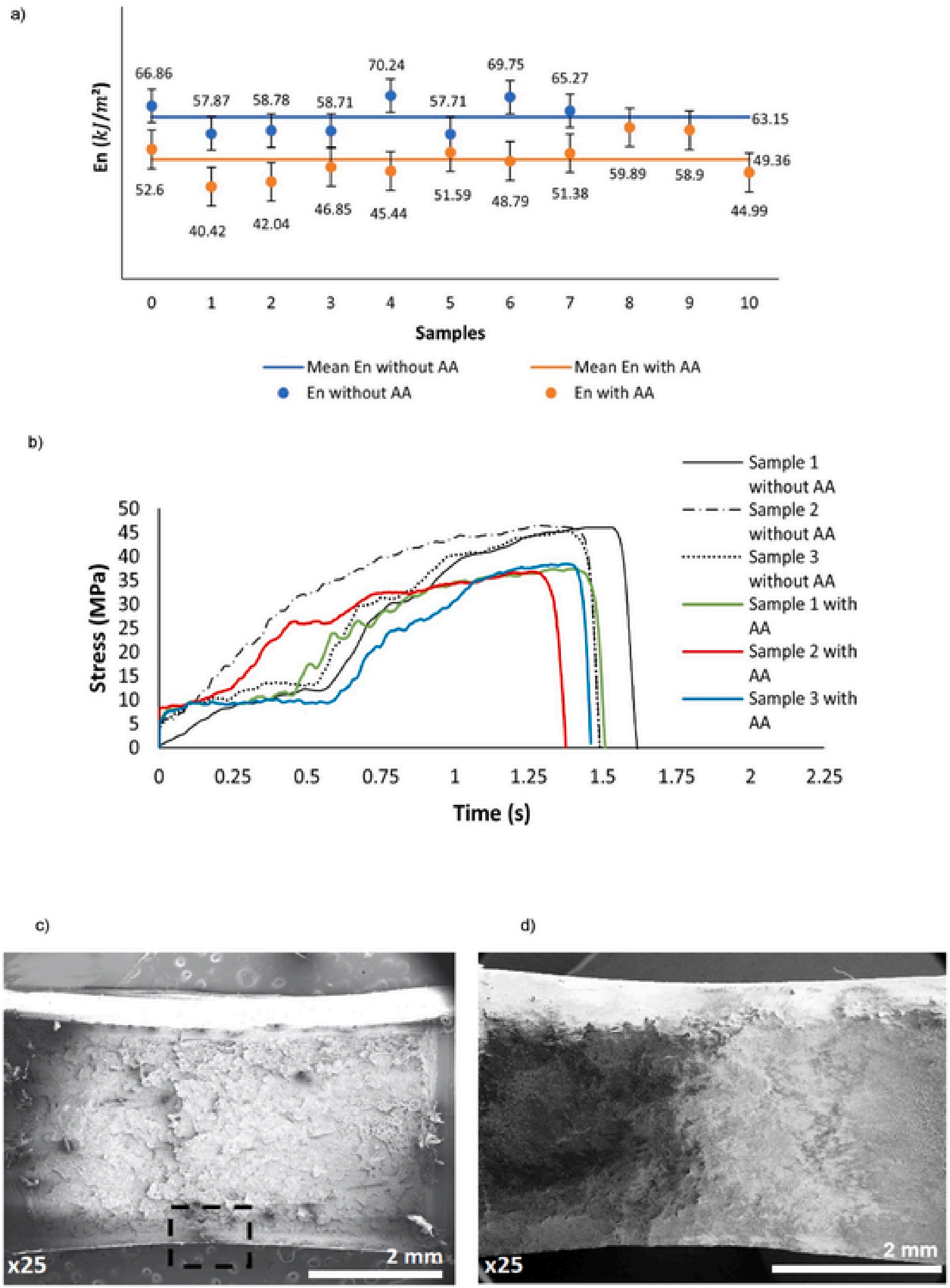

Fig. 5. a) Impact energy absorbed by each specimen; b) Stress vs Time for each specimen; c) SEM micrograph of the fractured region before AA; d) SEM micrograph of the fractured region after AA.

3.5. Resistance to traction and FEM maximum deflection assessment

In Fig. 7a, the stress-strain curve of BrHDPE material subjected to traction is represented. The results provide a $E_t = 950 \pm 80$ MPa; $\sigma_m = 45.5 \pm 2.2$ MPa and elongation $\varepsilon_y = 16.2 \pm 0.4\%$. It is not correct to compare the results obtained with virgin HDPE, as these materials undergo cross-contamination with traces of other polymers upon arrival at the landfill. However, the obtained elastic modulus falls within the range of virgin HDPE (0.8–1.6 GPa) (Reynoso et al., 2021).

a)

b)

Fig. 6. a) Previous coating scheme cross-cut test, from left to right Barnicoat 400E, Novolack and Novoacrilic. Upper schemes being sanded, and lower ones not sanded; b) Final coating scheme cross-cut test, from left to right Novolack and Barnicoat 400E, both previously sanded.

The results are higher than those obtained by Koriem et al. (2021) and Tesfaw et al. (2022), even the σ_y exceeds more than twice that of the author's rHDPE (0:100). The elongation ε_y reaches a value similar to the previous reference (8.5 mm, compared to 9.76 mm). The BrHDPE maintains its original stiffness as well as tensile strength, despite undergoing at least three cycles of heating above its melting temperature T_m. With this data, it is possible to determine the thickness of the manhole cover and the frame so as to achieve no more than the 6 mm of maximum deflection required by the standard. Fig. 7b shows the inverse proportional relationship between thickness and deflection. As shown, with a thickness of 39 mm, a maximum deflection of 6 mm is achieved.

4. Conclusions

The production process of urban manhole covers made 100% from a blended material combining two types of recycled HDPE means an important achievement for the circular economy in the area where this occurs, especially considering that one of the rHDPE is considered as dangerous because it contained oily residues from the petrochemical industry. To verify the feasibility of the use of these recycled materials the physicochemical, rheological, and mechanical properties have been analysed, far exceeding the limits required. Due to the volume of recycled HDPE generated, a blend was tested with a 50% weight mixture of both, whose results in the tensile impact test suffered a slight decrease of 21.84% in their mechanical properties after exposure to artificial aging. Regarding artificial aging, a coating guaranteeing that the material is unaffected by the different weather effects to which it will be exposed to during its application was developed and it was ensured that the flammability of the material is not modified by this coating. Finally, in order to verify the real behaviour of the coating, simulations were carried out applying static load hypotheses that did not exceed the maximum deflection indicated by the standard. The FEM analysis determined the minimum thickness required not to exceed this deflection and, thus, an adequate validation of the product was obtained for its application in A-15 and B-125 type covering devices. It can be expected that this new BrHDPE will be used to manufacture products exposed to the elements, such as street furniture that will be widely accepted in the market, avoiding the consumption of virgin raw materials. This alternative not only reduces the carbon footprint emitted to produce these types of products, but also offers a solution for the waste generated in an area as it becomes valuable and is given a second life.

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CRediT authorship contribution statement

M. Suffo : Supervision, Methodology, Software, Project administration, Writing – original draft. **M. Brey :** Conceptualization, Visualization, Investigation, Resources, Writing – review & editing, Resources. **J.P. Orellana :** Writing – review & editing, Software, Validation. **J.L. García-Morales :** Investigation, Writing – review & editing, Resources.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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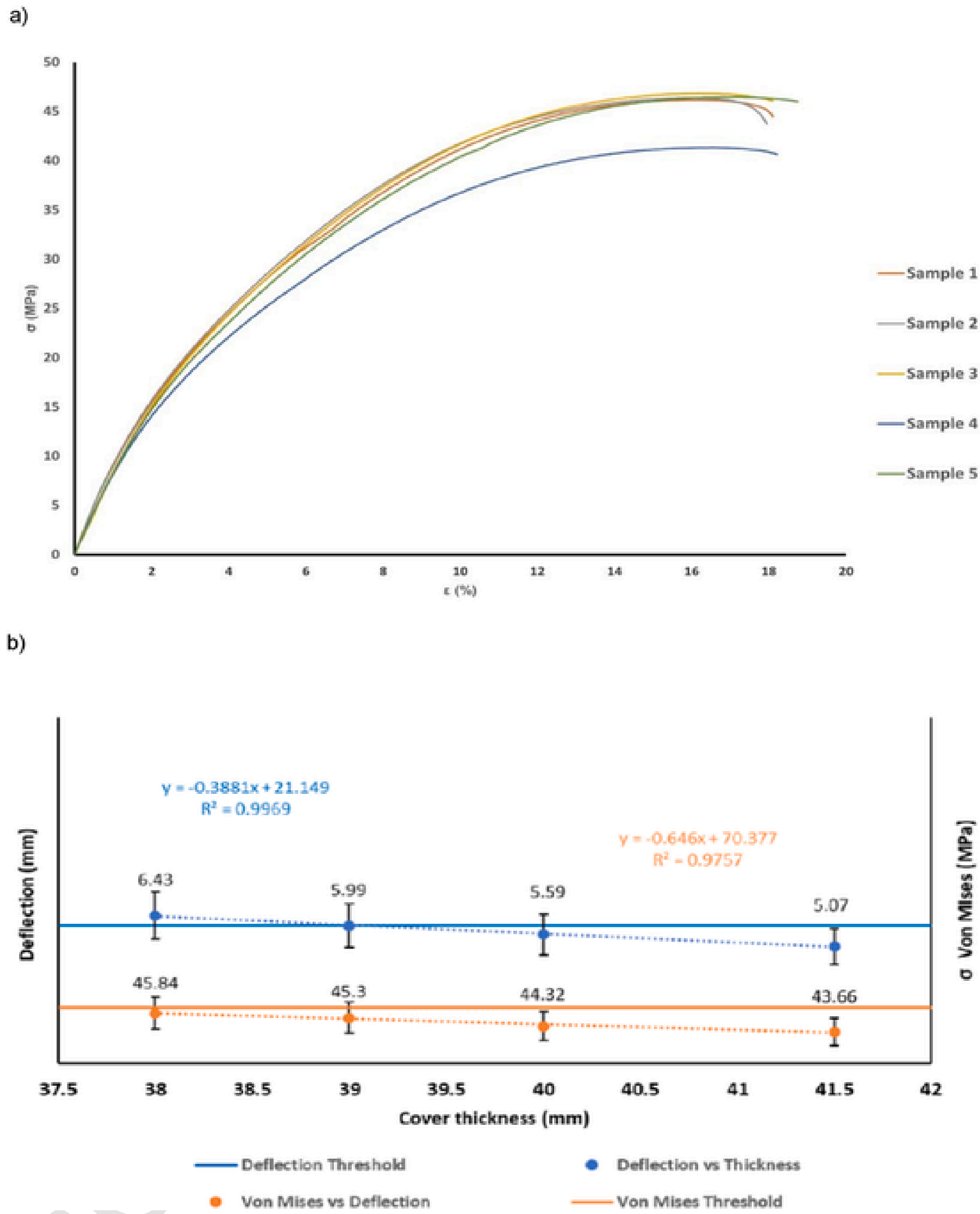

Fig. 7. Numeric simulations results: a) Stress-strain curves for tensile behaviour; b) Thickness verification and maximum deflection.

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