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Design, development and tested extrusion system for privacy LDPE tapes used in mesh fences

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ABSTRACT

In this research we provide a practical guide to achieve the successful extrusion of LDPE tapes commercially used in mesh fences, with controlled dimensions, good mechanical properties and weather resistance. Here we share: 1) The die design dimensions and its specialized slotted manufacture to get the veins of tape, 2) Processing temperatures profile, 3) Cooling method, 4) Hot stretch ratio (HSR), and 5) The effect of colorant and ultraviolet rays' protector, due to the outdoor use of polymer privacy tape. The formulated tape (0.8 wt. % UV protector and 5 wt. % colorant) showed the best performance under accelerated aging and reached good mechanical properties up to a time of 2000 hours compared to its initial values. The dye and the UV additive improved the mechanical properties. All of this led to obtain a LDPE tape to fulfill the expectative and characteristic of a commercial tape used for mesh fences.

Keywords: LDPE, plastic tapes, UV Protector Additive, Process design, mechanical properties.

INTRODUCTION

Low Density Polyethylene (LDPE) is widely used for many products. This is due to its properties such as low density, good transparency, impact resistance and high elongation [1]. Privacy plastic tapes used in mesh fences are one of the applications of LDPE, the industrial manufacturing of plastic tapes as well as many other plastic products is by extrusion process [2]. The production of any plastic product by extrusion process needs deep research (wide background) on the process design, machine design, process parameters, performance evaluation, and process planning for each extrusion product [3]. No one of the industries are able to reveal their research to public (new plastic producers). The development of industrial operation to produce privacy plastic tapes used in mesh fences by extrusion process involves as the main steps: the extrusion parameters, design of the die, cooling stage and tape stretch ratio.

Single-screw extruder offers relatively low investment cost and is the most common type of extruder [3]. During the processing of polymers, the extrusion parameters are crucial for the product quality. The appropriate selection of temperature profile, screw rotational speed and low-pressure drop in the exit will favor the additives homogeneity in the polymer matrix and will avoid polymer degradation and irregularities in the dimensions of the desired product.

The aim of an extrusion die is to distribute the molten polymer into the flow channel, with a uniform velocity and with a minimal low pressure drop. Through an extrusion die, the flow is subjected to the shear rate, high temperature and heat dissipation of molten polymer. If the die lips have a very small opening, the polymer requires high and uniform heating without dead zones, as this could alter the viscosity or cause thermal polymer degradation [2]. The efficiency of the extrusion die depends on the design and its geometry, as well as operating conditions during extrusion. The design of extrusion die is a complex task because the complex geometry (as shape, desired veins, etc.) of extruded product depends on it.

There are three cooling methods for extruded polymers: air, cooled rollers and water tanks. Water tanks are usually several meters in length and requiring large amounts of water, which is not favorable due to the low fresh water globally available [4]. The cooling stage in semicrystalline polymers accelerates crystallization and shrink them, also it has a direct effect on the mechanical and thermal properties of the final product [2]. During cooling stage, as well as in stretch stage, final product dimensions (width and thickness) and polymer chain alignment are defined [5].

Almost all research related to extruded polymer products focus to study the effect of a specific section of the extrusion process and its parameters as: profile temperatures [6], design of screw and its rotational speed [7], die design [8,9], cooling effect [4], pulling effect [5, 10,11] etc. But, to our knowledge, there are not publications in which a full extrusion process to produce a specific commercial product is detailed, due to economic interest.

In this research we provide a practical guide for the successful extrusion of LDPE tapes with controlled dimensions, mechanical properties and weather resistance using technical data that could be useful for the fabrication of plastic ribbon and sheets. Additionally, due to the outdoor use of polymer privacy tape in which sunlight causes deterioration, affecting mainly its mechanical properties, we studied the addition effect of ultraviolet rays' protector, under accelerated aging to provide a formulated tape with the best performance.

EXPERIMENTAL

Materials

The polymer used in this study was a LDPE homopolymer resin (BDL-92020), supplied by PEMEX (Mexico). The LDPE was stabilized with Irganox 1010 at 0.4 wt% to prevent thermo-oxidative degradation. Its melt flow index was 2 g/10 min (190 °C/2.16 kg), calculated according to ASTM D1238. Green colorant J-24332 (Masterbatch) and UV protector additive J-34219 were purchased at Chemical Color (Mexico).

Extrusion parameters

A 40 mm single-screw extruder (Leneded) was used to conduct the methodology. Temperature profile was chosen to ensure the polymer melt flow through the small gap in the exit of the die. Temperature profile was set in the feed section at 125 °C to reach 200 °C at the die. The tapes were extruded, cooled at a cooling tank and drawn using a four-roll puller. Table 1 shows the details of screw extruder.

Flow rate and pressure drop measurements

The flow rate of the LDPE extrudate was controlled by the screw rotational speed (20, 30, 40 and 50 rpm). Pressure and temperature sensors (HENENG:model PT124,Tekno Powers:Tcx-200-j) were placed in the die. Flow rate values were measured once the steady state conditions were reached (about 6 min at a constant screw speed rotation) at intervals of 2 min once both pressure and temperature were stable. The weight of three samples, for each rotational speed, was averaged and the mass flow rate was converted to volumetric flow rate (Q) and eventually shear rate. The Δp was recorded for each rotational speed.

Measurements of viscosity online

The LDPE viscosity online was measured directly from the extrusion system (described in previous section) using a methodology similar to that reported by Wu [12], who used a slit rheometer adapted a single screw extruder. The author found a good correlation for the unfilled polymer: the viscosities obtained at low frequency with a rotational rheometer; followed the viscosity curve with the ones obtained online. Wu did not observe this behavior for the filled homopolymer with calcium carbonate.

Only one melt pressure transducer was used. At the exit of the die, the pressure is 1 atm. The drop of pressure is the difference between the recordings of the transducer and 1 atm. The drop pressure is mainly due to the proposed die because it has the narrower gap through its length. With the pressure drop the viscosity was calculated. The distance of the transducer to the end of the die was of 10 cm.

Cooling in the water tank

The chosen cooling method involves a bath with a length of more than 3 m and a water tank with a capacity of 180 liters (Figure 1). Concerned to the low fresh water globally available, water from the water tank near the extruder die was pumped to a heat exchanger to lower its temperature and the water was returned to the water tank in the center. The cooling has a direct effect in the crystallization of the semicrystalline LDPE. The cooling leads to a shrinkage, reducing the cross section of the extruded tape. Temperature was set at ≤ 50 °C in the cooling tank, to prevent deformation and degradation of plastic tape. The heat exchanger employed was the type used in the automotive industry (radiator) together with an air extractor, the hot water from the water tank was introduced to this heat exchanger, effectively reducing the temperature. Of this way, it was not necessary to use frequently fresh water (from urban water service) to reduce the temperature, neither to send the hot water to a storage tank for subsequent reuse. It was not required to use high-cost and electrically consuming equipment for the cooling system such as a chiller.

Accelerated aging study

For this study, the samples consisted of extruded tapes at 40 rpm, formulated as shown in Table 2. UV ray's protector and colorant were incorporated in the hopper of the extruder.

Characterization

A Perkin Elmer Infrared Spectrometer coupled with a diamond ATR cell (FTIR), a NEXUA model 470 was used to characterize UV protector and dye samples. A wavelength range from 4000 to 400 cm^{-1} was used.

Rheological properties were studied using an Anton Paar Physical MCR501 rheometer, the experiments were carried out at 200 ºC. The rheometer was equipped with concentric disk plate-plate geometry. The diameter of the plates was 25 mm and the gap about 1 mm. The measurements in rotational modus were carried out under dry nitrogen atmosphere.

The plastic tapes underwent accelerated aging according to the ASTM G154 method in an UV Weathering Resistance Test Chamber Q-LAB model QUV/SPRAY. After the accelerated aging the plastic tapes were mechanically tested. Tensile strength and elongation-at-break were obtained according to the ASTM D638 method (tested specimens were type IV) with a Shimadzu AG-20kN universal machine.

RESULTS AND DISCUSSION

Design of the tapes die

Figures 2a and 2b show the bottom and top of the desired tape. The veins (lines) alternate on both sides. The desired thickness on channel is 0.65 mm and 1.0 mm including height vein. The standard width is 61 mm. These characteristics were considered for the die design.

Different die types were tested, with those we observed that, the effects of stretching and cooling in the water tank (at 50 °C), as well as the drop of the tape into the water tank reduce the tape dimension (in a coming paper we will show the effect of comparison of the different hot stretch ratios studied). The total thickness reduction owing by those effects was of 20% and the width reduction was 50%. Due to those effects, the final die was designed with an additional opening in its lips of 20%, the height of the veins was also 20% greater than desired tape and the die width almost double of the desired product (see Figure 3). The details of the die and its dimensions are shown in Figures 4a-4d.

The first die tested was a rectangular slot without slots (not serrated) to obtain a smooth strip of the same thickness across its width. With this kind of die, we also observed that the total thickness reduction was of 20% and the width reduction was also 50% during the drop to the water tank.

Rheology

The results obtained with the rotational rheometer are shown in Figure 5a. The results showed that the LDPE behaved like a pseudoplastic fluid. The shear thinning behavior for LDPE starts at low shear rate or frequency [13], in this case the power law region started at a shear rate of 1 s^{-1}. The parameters of power law of viscosity at 200 ^{o}C [14] were like follows: the parameter of consistency “m” was of 6155.8 Pa.s^{n} and the pseudoplasticity index “n” was of 0.45.

Estimation of the shear rate at the different screw rotational speeds

The shear rate $\dot{\gamma}$ [15] was evaluated with using the equation $\dot{\gamma} = \frac{\pi DN}{H}$: where D is the screw diameter, N is the screw speed and H is the channel depth in the metering section of the extruder. The shear rates obtained are reported in Table 3.

The shear rate was relatively low in the channels of the extruder (the values were between 16.76 and 41.89 s^{-1}), however these values fall in the range in polymer extrusion processes. Greene [16] point out that the shear rates in extrusion are in the range of 100–500 s^{-1}.

Flow rate and pressure drop results

The designed die was of multiplate type (see Figure 6a), and the melt pressure was recorded for all the experiments. The pressure transducer and thermocouple can be observed in Figure 6b.

Table 4 shows the results of volumetric flow rate (Q) and pressure drop (ΔP).

Q was calculated according to stablished in the experimental part. The pressure drops were recorded with the melt pressure transducer at the end of the extruder.

A fairly satisfactory and not very restrictive die design was obtained, as can be seen in Table 5. This table shows the volumetric flows rates with and without die for the different rpm used. The flow rate drop for the different conditions was between 7.69 and 14.86%, which means that the decrease in flow rate was not very high (significant).

Measurement of the viscosity online

The methodology used by Wu [12] was followed to obtain the pseudoplasticity index (n) and the non-Newtonian viscosity. The slit thickness is ¨2H¨, the die width is ¨2W¨ and its length is ¨L¨.

The shear rate evaluated at the wall is expressed by [12]:

$$\dot{\gamma} = (2 + \frac{1}{n})\frac{Q}{4WH^2} \qquad [1]$$

Where ¨n¨ is the pseudoplasticity index

This index is the slop of the wall shear stress (H.ΔP/L) versus $Q/4WH^2$ on a log-log plot (see Figure 5b). The obtained value of ¨n¨ was 0.33.

The viscosity is by definition expressed by:

$$\eta = \frac{\sigma}{\dot{\gamma}} \qquad [2]$$

From Figure 5a, it can be seen that the viscosity values obtained online are very close to those obtained with the rotational rheometer. Using a slit die equipped with 3 pressure transducers, Nguyen et al [17] reported the viscosity of recycled HDPE measured online. They observed that the values of the viscosity measured online were lower than those obtained with a capillary rheometer, but slopes of the viscosity curves of both measurements were very similar. Wu [12] observed that the unfilled polypropylene followed Cox-Merz rule whereas the filled polymer did not follow the viscosity curve at high shear rate.

Stretching of tape

After the cooling tank stage, the tape passed through the puller and was coiled. The pulling (at any speed) produces a reduction in the extruded tape cross section and then the thickness is diminished, thus, controlling the stretch velocity is decisive for desired tape dimensions. The desired thickness is 0.80 mm and the standard width is 61.00 mm. For optimal control of the thickness and width of the tape, a variable-frequency drive (VFD) was adapted in the puller. An encoder was incorporated into this puller to record the meters of tape produced (see Figures 7a and 7b).

The term "hot stretch ratio" (HSR) was used to explain the results of the pulling of the tape. This term is given as the difference between the linear velocity of the rolls (V_R) and the linear velocity of the extrudate (V_E) divided by the velocity of the extrudate:

$$HSR = (V_R - V_E)/V_E \qquad [3]$$

The velocity of the puller rolls (V_R) can take a range of values due that the tape was extruded between rotational screw speeds of 20 and 50 rpm (see Table 6).

The advantage to use the term HSR, is that the latter almost remains constant for different conditions of rotation of the extruder and then the linear velocity of the rolls (V_R) can be calculated for different flow rates through the extrusion die obtaining the desired width and thickness of the polyethylene tape.

From Table 6, it can also be observed that the first value of HSR obtained at a rotational screw speed of 20 rpm (which was taken to estimate the V_R´s values at other screw speeds) and the experimental ones obtained between 30 rpm and 50 rpm respectively are very similar. These results showed that the velocity values of the puller rolls can be predetermined satisfactorily with equation 3, obtaining the desired dimensions of the polyethylene tape.

Characterization of the UV additive

It has been shown that the main cause of damage to plastic films exposed to the elements is due to ultraviolet light. Studies show that significant results have been obtained by prolonging the durability of plastic products exposed to solar radiation using UV additives [18]. An effective strategy to improve the ability of plastics to resist UV aging is the use of UV absorbers as additives in plastics. The UV protector and colorant for the polymer consisted of a blend of polyethylene and $CaCO_3$. Figure 8 shows the FTIR spectra of as received UV protector additive and colorant. The blue line shows the spectrum of UV protector in which are clearly visible the presence of calcium carbonate ($CaCO_3$) bands at 715, 880, 1490, 1735, 1804, 2530, 2900, and 2998 cm^{-1} [19]. The peaks at 2916 cm^{-1} and 2849 cm^{-1} are related to asymmetric and symmetric C-H stretch of the methylene groups CH_2 in the polyethylene polymer [20]. The red line shows the spectrum of green colorant, as mentions above there are peaks associated to polyethylene and $CaCO_3$, the other peaks are related to the phthalocyanine green, a pigment commonly used for polymers [21].

Accelerated aging

The objective of these tests is to obtain the best performance formulation for privacy tape used in mesh fences. The outdoor use of polymer privacy tapes exposes them to sunlight, it causes deterioration, affecting mainly its mechanical properties [22]. Accelerated aging simulate the environment (atmosphere with UV radiation and condensation), the formulated samples (Table 2) were exposed to an accelerated aging for a certain time. The samples were subjected to elongation- and tensile strength-at-break tests, respectively. These properties were evaluated after samples were exposed to an accelerated aging (see figures 9-12).

The usable life of a film (tape) is the time required for a reduction by 50 % of the average property analyzed during natural or accelerated aging of the initial value in this property (t_{50}), [23].

Tensile Strength

Figure 9 shows the results for tapes without dye (colorant) for accelerated aging of tensile strength at break of samples 1, 2 and 3. The sample 1 without UV protector showed at a time of 170 hours a tensile strength value of 12 MPa which represent the 50% of its initial value (22 MPa at 0 hours). For sample 2 (0.4 wt% UV additive) and sample 3 (0.8 wt% UV additive) exposure times of 1125 and 1875 hours were required, respectively, to lose 50% of their initial values in this property. Sample 1 was also evaluated without exposure to accelerated aging and its value was 22 MPa.

Figure 10 shows the results for tapes with dye (colorant) for accelerated aging of tensile strength at break of samples 4, 5 and 6. The sample 4 (with 5 wt.% dye and without UV additive), sample 5 (with 5 wt. % dye and 0.4 wt. % UV additive) and sample 6 (with 5 wt. % dye and 0.8 wt. % UV additive) showed a loss of 50% of the initial value in this property at a times of 200, 850 and 2000 hours of exposure, respectively.

The sample 6 showed the superior performance for tensile strength, owing by the 5% of dye added. As reported by Saron and Felisberti, the additional stability of the tape indicates good chemical interactions with the dye [24].

Elongation-at-break

The elongation-at-break results of samples without dye are shown in figure 11. Results of samples without UV protector showed a very poor performance in this property. At a time of 125 hours the elongation value at break was 360% (which is the 50% of its initial value in this property) compared to an initial value of 720% (for sample 1 without exposure to accelerating aging). For the sample 2 with 0.4 wt. % UV protector and for the same value of 50% of the initial value it showed 860 hours in this property. Sample 3 with 0.8 wt.% UV protector showed a value of 360 % in elongation-at-break (50% of initial value) in an exposure time of 1550 hours.

The elongation-at-break results of samples with dye are shown in figure 12. Results of sample 4 with 5 wt. % of dye and without UV protector showed 360% of elongation-at-break which is the half of its initial value at a time of 250 hours, the sample 5 (with 5 wt. % of dye and with 0.4 wt. % UV protector) and sample 6 (with 5 wt. % of dye and with 0.8 wt. % UV protector) showed respectively times of 700 and 1740 hours at 50% of the initial value in this property.

As same as showed for tensile strength test the sample 6 showed the superior performance for elongation-at-break. This is also related to the chemical interactions with dye [24].

Murayama et al. [25] have elongated extruded HDPE films obtained by blown film process. The elongated HDPE film was obtained by heat elongation of the extruded film at 100 ◦C. They found that the tensile strength increased from 35 MPa to 170 MPa by an induced hot elongation around 400%. These results corroborate our findings where some samples showed high elongation values and important tensile strength improvements.

Akdogan and Şahbaz [26] have deformed flat plate-shaped HDPE specimens by compression molding. Plastic deformation rates ranged from 0 to 50%. These authors have observed that the highest values in tensile strength and elongation-at-break occurred for a deformation rate of 10%. These results agree with the ones reported in this research, where some samples showed improved tensile strength and elongation-at-break.

CONCLUSION

The proposed extrusion process allowed to obtain the desirable dimensions and veins of the tape as well the quality of the final product was achieved. The changes in volumetric flow rate were not significative with and without dye, due to a nonrestrictive die design. The length of the dye led to low pressure drops.

The temperature in the water tank must be lower than 50°C. Hot water from the water tank was send to a heat exchanger which effectively reduce the temperature of water to incorporated again in to the water tank. Implementing this system avoid the use of large amounts of water from the urban service.

In accelerated aging tests, the best performance was for the sample 6 with 5 wt. % of dye and 0.8 wt. % UV protector. This sample reached good mechanical properties up to a time of 2000 hours compared to its initial values. The dye and the UV additive improved the mechanical properties.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

1. Pham NTH (2021) Characterization of low-density polyethylene and LDPE-based/ethylene-vinyl acetate with medium content of vinyl acetate. Polymers 13: 2352 [CrossRef]
2. Lee F. Samler, Polyethylene Tape Extrusion, US Patent 2,499,421
3. Hyvärinen M, Jabeen R, Kärki T (2020) The Modelling of Extrusion Processes for Polymers—A Review. Polymers 12: 1306 [CrossRef]
4. Mitroshin VN, Mitroshin YV (2016) Optimal control of cable insulation cooling at extrusion line. 2016 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM): 1-4 [CrossRef]
5. Rodriguez-Gonzalez FJ, Virgilio N, Ramsay BA, Favis BD (2003) Influence of melt drawing on the morphology of one- and two-step processed LDPE/thermoplastic starch blends. Adv Polym Technol 22: 297-305 [CrossRef]
6. Luo C (2020) Modeling the temperature profile of an extrudate in material extrusion additive manufacturing. Mater Let 270: 127742 [Crossref]
7. Christiano, JP (2012) Examination of the performance of a high speed single screw extruder for several diferent extrusion applications. In: Proceedings of the Annual Technical Conference—ANTEC, Conference Proceedings, Orlando, FL, USA, 2
8. Liu YM (2012) Plastic Parts Die Design Analysis. Appl Mech Mater 246-247: 956-995 [CrossRef]
9. Huang Y, Gentle CR, Lacey M, Prentice P (2000) Analysis and improvement of die design for the processing of extruded plastic pipes. Mater Des 21: 465-475 [CrossRef]
10. Liang JZ (2019) Melt strength and drawability of HDPE, LDPE and HDPE/LDPE blends. Polym Test 73: 433-438 [CrossRef]
11. Rodriguez-Gonzalez F, Ramsay BA, Favis BD (2004) Rheological and thermal properties of thermoplastic starch with high glycerol content. Carbohydr Polym 58: 139-147 [CrossRef]
12. Wu Min, (1999) Effects of dispersion on rheological properties of filled polypropylene, Master Thesis, Polytechnique de Montreal, Canada
13. Djellali S, Sadoun T, Haddaoui N, Bergeret A (2015). Viscosity and viscoelasticity measurements of low density polyethylene/poly(lactic acid) blends. Polym Bull 72: 1177-1195 [CrossRef]
14. Christopher W. Macosko, (1994) Rheology principles, measurements and applications, Wiley-VCH, ISBN: 1-56081-579-5

15. Tadmor Zehev and Gogos Costas G, (2006) Principles of polymer processing, Editorial Wiley, 2nd Edition.
16. Greene J (2021) Rheology and plastic flow. In: Automotive plastics and composites, pp.: 57-69 [CrossRef]
17. Nguyen BK, McNally GM, Clarke A (2014) Real time measurement and control of viscosity for extrusion processes using recycled materials. Polym Degrad Stabil 102: 212-221[CrossRef]
18. Qiao RM, Zhao CP, Liu JL, Zhang ML, He WQ (2022) Synthesis of novel ultraviolet absorbers and preparation and field application of anti-ultraviolet aging PBAT/UVA films. Polymers 14: 1434 [CrossRef]
19. Zapata P, Palza H, Díaz B, Armijo A, Sepúlveda F, Ortiz JA, Ramírez MP, Oyarzún C (2019) Effect of $CaCO_3$ nanoparticles on the mechanical and photo-degradation properties of LDPE. Molecules 24: 126 [CrossRef]
20. Kochetov R, Christen T, Gullo F (2017). FTIR analysis of LDPE and XLPE thin samples pressed between different protective anti-adhesive films. 2017 1st International Conference on Electrical Materials and Power Equipment (ICEMPE) [CrossRef]
21. Barni D, Raimondo L, Galli A, Caglio S, Mostoni S, D'Arienzo M, Martini M, Sassella A (2022). Separating pigments and fillers from the polymer matrix in acrylic colors subjected to natural aging. Eur Phys J Plus 137: 926 [CrossRef]
22. Ovalı S, Sancak E (2020) Investigating the effect of the aging process on LDPE composites with UV protective additives. Journal of Thermoplastic Composite Materials 35: 1921-1939 [CrossRef]
23. Ramirez E, Martinez JG, Sanches S, Balderas CL (1995) Prediction of useful life of greenhouse films with artificial ageing equipment. Plasticulture 105: 5-12
24. Saron C, Felisberti MI (2006) Influence of colorants on the degradation and stabilization of polymers. Química Nova 29: 124-128 [CrossRef]
25. Murayama T, Abe E, Saito H (2021) Strengthening of mille-feuille structured high-density polyethylene by heat elongation. Polymer 236: 124343 [CrossRef]
26. Mao Q, Su B, Ma R, Li Z (2022) Investigation of tensile creep behavior for high-density polyethylene (HDPE) via experiments and mathematical model. Materials 14: 6188 [CrossRef]

Table 1. Details of the screw extruder.

Barrel diameter	40 mm
Flight angle	22°
Screw length (metering section)	350 mm
Channel depth (metering section)	2.5 mm
Screw pitch	36 mm
Flight wide	9 mm

Table 2. Tape formulations.

Sample (LDPE)	UV ray's protector wt.%	Colorant wt.%
1	0	0
2	0.4	0
3	0.8	0
4	0	5
5	0.4	5
6	0.8	5

Table 3. Generated shear rates in the metering section of the extruder.

Screw rotational speed (rpm)	Shear rate (s^{-1})
20	16.76
30	25.13
40	33.51
50	41.89

Table 4. Q and ΔP values for the different screw rotational speeds.

Screw rotational speed	Die dimensions	Q (cm^3/s)	ΔP (MPa)
20	2W=12cm, 2H=0.08cm,	1.44	3.6 MPa
30	2W=12cm, 2H=0.08cm	1.89	3.8 MPa
40	2W=12cm, 2H=0.08cm,	2.67	4.3 MPa
50	2W=12cm, 2H=0.08cm,	3	4.6 MPa

Table 5. Restriction percent in flow rate caused for the die at the different screw rotational speeds.

Screw rotational speed	ΔP with die (Mpa)	ΔP without die (Mpa)	Q with die (cm^3/s)	Q without die (cm^3/s)	Restriction percent
20	3.6	1.5	1.44	1.67	13.72%
30	3.8	1.6	1.89	2.22	14.86%
40	4.3	1.8	2.67	2.9	8.61%
50	4.6	2	3	3.25	7.69%

Table 6. HSR, V_R and V_E for the different screw rotational speeds.

Screw rotational speed	Q (cm^3/s)	V_E (cm/s)	V_R (cm/s)	HSR evaluated at 20rpm (reference)	HSR experimental
20	1.44	1.50	4.05	1.70	1.70
30	1.89	1.97	4.84	1.70	1.46
40	2.67	2.78	7.69	1.70	1.77
50	3	3.13	8.97	1.70	1.86

Figure 1. Cooling water tank.

(a) (b)

Figure 2. (a) View of the tape (upside), (b) View of the tape (down side).

Figure 3. Fall of the tape into the water tank.

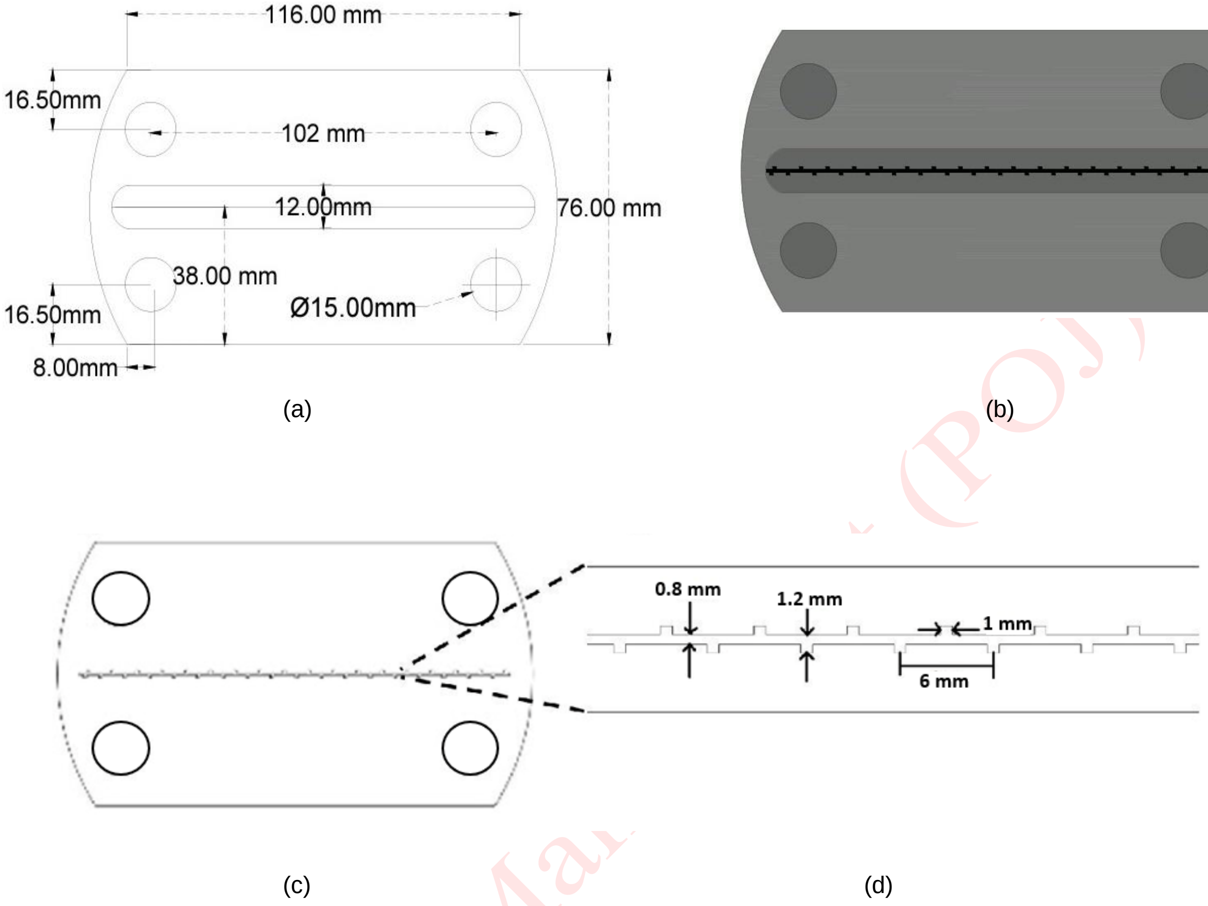
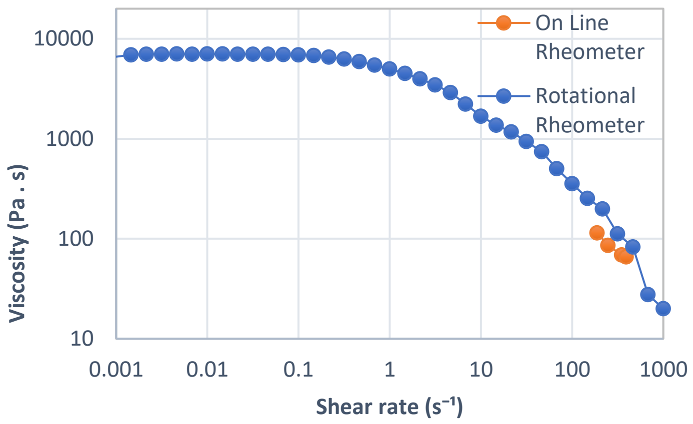
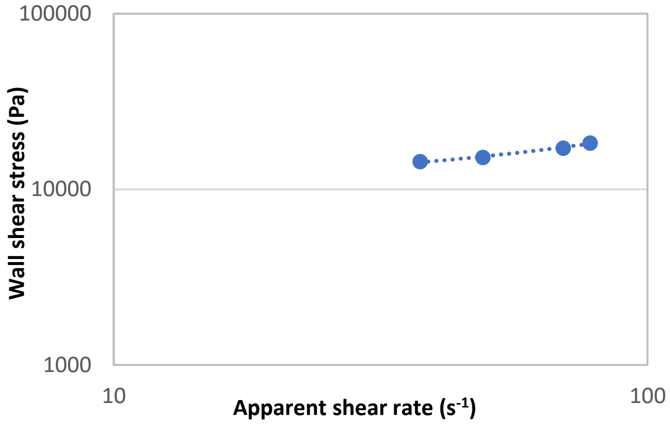


Figure 4. (a,b) Shows inner side die design with detailed dimensions, (c,d) shows the outer side die design with detailed dimensions.



(a)

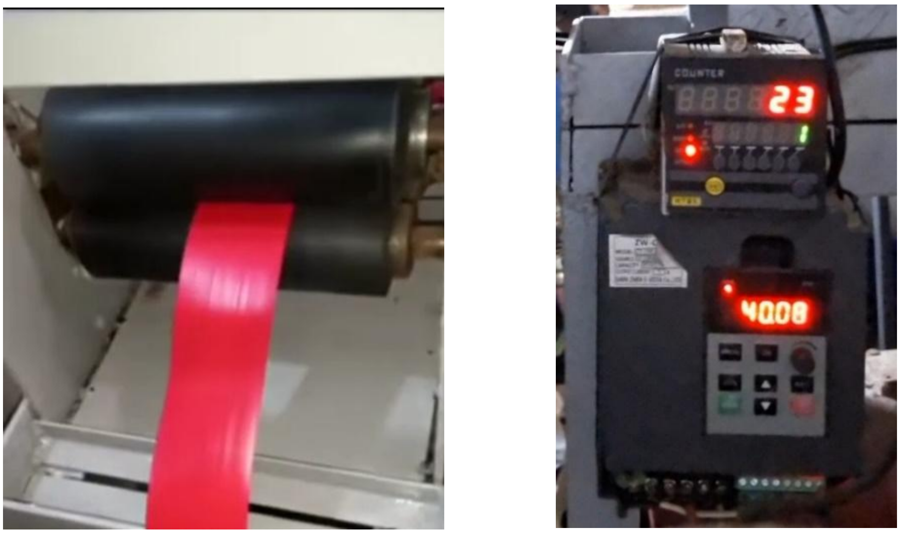


(b)

Figure 5. (a) Viscosity versus shear rate for LDPE at 200 ºC, (b) wall shear stress versus apparent shear rate (Q/4WH^2).

(a) (b)

Figure 6. (a) Multiplates type die, (b) Instrumented extruder head.



(a) (b)

Figure 7. (a) Four rolls puller, (b) Encoder and VFD.

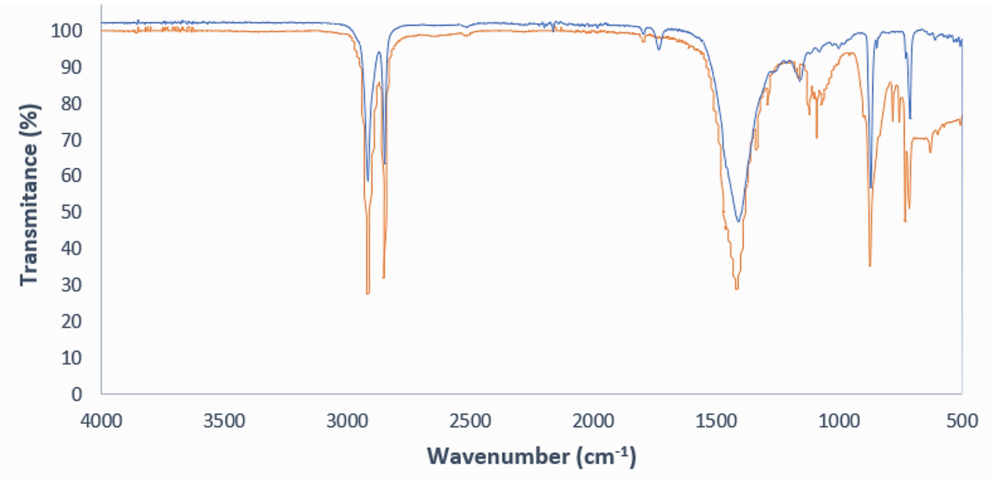


Figure 8. FTIR spectra of the UV protector additive and colorant, respectively. UV in blue and colorant in red.

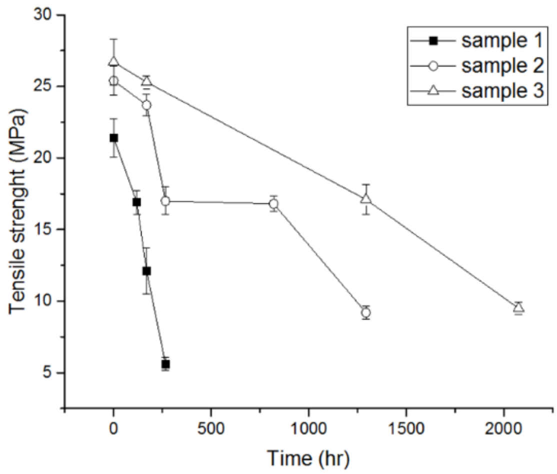


Figure 9. Tensile strength-at-break for samples 1, 2 and 3.

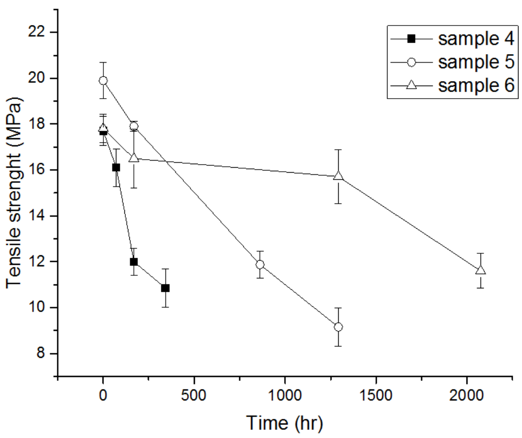


Figure 10. Tensile strength-at-break for samples 4, 5 and 6.

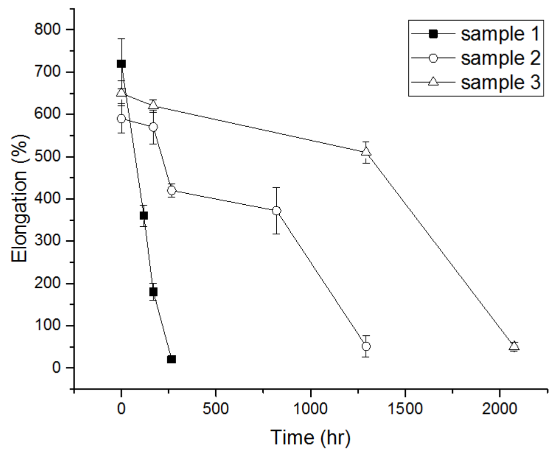


Figure 11. Elongation-at-break for samples 1, 2 and 3.

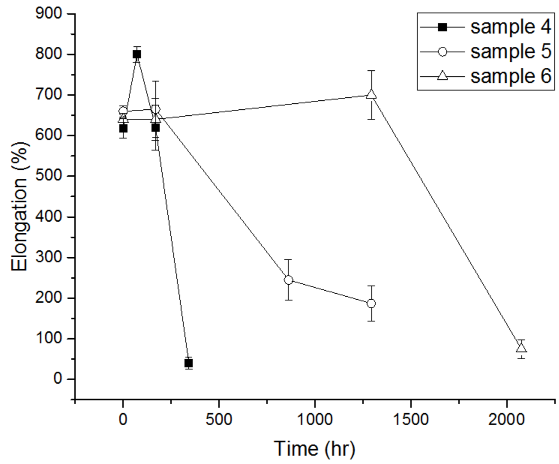


Figure 12. Elongation-at-break for samples 4, 5 and 6.