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A new approach for silane curing polyolefin elastomer/linear low density polyethylene blends by Monosil and Sioplas processes

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ABSTRACT

Silane cross-linking of metallocene-based polyethylene-octene elastomer (POE)/linear low density polyethylene (LLDPE) blend was carried out using the single-step Monosil process and two-step Sioplas process in an industrial scale twin-screw extruder. The study revealed that benzoyl peroxide (BPO) is a better initiator than dicumyl peroxide (DCP) for grafting reaction of vinyl trimethoxysilane (VTMS). The optimum values of compression set, gel content and tear strength which were, respectively, found to be 40.4%, 79% and 22.6% obtained at 0.2 w% of BPO. Addition of 0.3 w% antioxidant cause the curing time decreased from 14 to 16 h to 8 h. Oit of the sample was increased linearly with increasing the antioxidant content up to 0.5 w%. The effect of dibutyltin dilaurate (DBTDL) as catalyst on the melt flow index (MFI) of the silane grafted compounds, with the aim of selecting an appropriate silane grafting process, was investigated. The results showed a MFI= 6.4 g/10 min for the silane grafted compound obtained from the Sioplas process, but, MFI= 1.9 g/10 min which was due to the presence of the catalyst in the Monosil process indicated that this method is not a promising process for silane grafting.

HIGHLIGHTS

- Silane crosslinking POE/LLDPE blend was carried out using the Monosil and Sioplas processes in a twin-screw extruder.
- BPO is better initiator for grafting reaction of VTMS than DCP.
- The curing time required for confirming hot set test was decreased from 14 to 16 h to 8 h by addition of 0.3 wt% antioxidant, Irganox 1010.
- OIT time increased linearly with increasing the antioxidant concentration.
- Sioplas process caused lower crosslinking degree as well as minimum pre-crosslinking, which prevented the formation of gell spots and rough surface.

ARTICLE HISTORY

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KEYWORDS

POE/LLDPE blend; Sioplas process; Monosil process; pre-crosslinking; silane grafting

1. Introduction

Thermoplastic elastomers (TPEs) are materials having the processability behavior similar to thermoplastics and the properties similar as cross-linked elastomers.^[1,2] These materials may be copolymers or they may be physical mixtures of a thermoplastic polymer with an elastomer, in which each component has its own unique properties. TPEs exhibit elastomeric behavior along with the melt process ability of thermoplastics. This dual behavior of TPEs has opened a new field in polymer science.^[3–7] The thermoplastic polyolefin elastomers (POEs) family has a significant role in growing the TPEs markets. The use of POEs in automotive industry is widely adopted due to the extensive variety of their products, desirable price/performance relationship and easy production method. Polyolefin thermoplastic compounds based on blends of polyolefin elastomers and semi-crystalline polyolefin have become more popular.^[8] Due to the advantages of high tensile strength, good environmental

crack resistance, high toughness and excellent dielectric properties, low density polyethylene (LDPE) and linear low density polyethylene (LLDPE) are widely used in blends and composites.^[7,9,10] In general, POEs have low degree of crystallinity and low density, which make them soft and flexible materials. Non cross-linked POEs lose their dimensional stability and flow easily at the temperatures higher than the melting point of their crystalline phase. In addition, the melting point and hardness of POEs reduce with decreasing their density and degree of crystallinity. Therefore, a lower melting point is expected for soft POEs. POEs are usually cross-linked to ensure that they maintain their stability and mechanical properties above the melting point of their crystalline phase.^[11,12] In industry, the cross-linking process is generally performed by using peroxide or silane compounds, and sometimes through electron beam cross-linking processes.^[11,13,14] Nonetheless, cross-linked POEs tend to exhibit poor compression and tension set. Thus, certain improvements are needed in the field of cross-linkable polyolefin

elastomers.^[11] The cross-linking using silane grafting reagents is one of the most common methods for improving the properties of polyolefin elastomers.^[5,6] Easy processing, low capital investment and favorable properties of processed materials are the advantages of using silane cross-linking method.^[6,13–15] The Monosil and Sioplas processes are two of the major technologies in the manufacturing of silane cross-linked materials. Synthesis ethylene-silane copolymers and dry silanes are alternatives to the Sioplas and Monosil processes, respectively.^[16] Monosil process is a one-step process, which was announced by BICC Limited and Establishments Maillefer SA in 1974.^[17] This process was originally termed as Monosil, but nowadays it is also known as the Nokia-Maillefer process.^[18] In this process, all materials are fed directly into extruder, so there is not risk of premature and excessive cross-linking. However, some disadvantages of this process are the need to high initial investment, high-skill members and extensive operation training for managing and reducing scraps. In this process, the reaction formulation is critical because some compositions in the reaction system may be interfere with the grafting reaction.^[19] Sioplas process was developed by Midland Silicones Co. (Dow Corning Co.) in 1968.^[20] The first and most critical stage of this process is the peroxide-activated grafting of a vinyl silane onto the polymer chains which is usually carried out in compounding equipment such as a co-rotating twin screw extruder. In the next step, a blend of ~95 parts of single grafted copolymer and ~5 parts of catalyst master batch is prepared by metering or either tumble blending which is then converted into pipes, cables or other finished parts in conventional forming extruders, or by injection or extrusion blow molding.^[16] The product is cross-linked in a steam bath under the action of temperature and humidity.^[14,16] Sioplas method has some disadvantages because it is a two-step procedure with limited shelf life and high raw material costs as well as risk of pre-crosslinking on the surface of pellets during storage. While the advantages of this method are fast curing, versatility of base resins (i.e., LDPE, Ethylene vinyl acetate (EVA), Ethylene propylene rubber (EPR) and so on), low capital investment and also no need to special equipment. Limited use of some additives, handling of hazardous liquid chemicals, high scrap rates, high capital investment and the requirement for specific equipment are the disadvantages of the Monosil method. Nevertheless, the advantages of this method are low material cost, versatility of base resins, fast curing, and that it has no shelf life problem. It also should be noted that the molten flow index decreases with the proceeding of the silane grafting reaction.^[16]

In this work, silane cross-linking of POE/LLDPE blend was carried out using the single-step Monosil and two-step Sioplas processes. Silane grafting process was carried out by an industrial scale twin-screw extruder. The effect of organic peroxides of dicumyl peroxide (DCP) and benzoyl peroxide (BPO), as the initiators of the grafting reaction of vinyl trimethoxysilane (VTMS), and their concentration on the mechanical and thermal properties of the products were investigated. Also, the effect of thermal antioxidants on the

composite stability was studied. For the shaping of the final product, it was needed to re-extrude the obtained silane grafted compounds before its pre-crosslinking. Therefore, with the aim of selecting the type of silane method, Monosil or Sioplas process, the effect of dibutyltin dilaurate (DBTDL) as catalyst on the melt flow index (MFI) of the silane grafted compound was investigated.

2. Experimental

2.1. Materials

POE was supplied as pellets from SK Global Chemical Co., Ltd, South Korea. It has a nominal melting index of 5 g/10 min at 190 °C, a density of 0.868 g/cm³ and mooney viscosity (ML 1 + 4@121 °C) of 8 MU. LLDPE was purchased as pellets from Amir Kabir Petrochemical Co., Ltd, Iran. It has a nominal melting index of 0.9 g/10 min at 190 °C and 2.16 kg piston force, as well as a density of 0.921 g/cm³ and vicat softening point of 100 °C. VTMS was supplied by RUI Chemical (China). Dicumyl peroxide and benzoyl peroxide, the initiators, were purchased from Coin AKZO Nobel Co. (Netherlands) and Arkema (France), respectively. DBTDL, the catalyst, was purchased from Merck (South Korea). Pentaerythritol tetrakis (3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate), Irganox 1010 antioxidant, was supplied by BASF Co., Germany.

2.2. Sample preparation

The silane grafting process of the POE/LLDPE blend was carried out in a co-rotating twin-screw extruder (Model CTE 65, COPERION Co. Germany). The extruder has twelve heating/cooling zones. A constant screw speed (30 rev min⁻¹) and feed rate (3.5 kg/h) by using a temperature profile of 170–210 °C from feed zone to die zone were used. A constant silane concentration of 5 w% was used, while, the concentration of the peroxide was varied in the range of 0.1–0.3 w%. In the next step, a blend of the single grafted copolymer (~95 w%) and the catalyst master batch (~5 w%) was prepared with an injection molding equipment. A catalyst master batch consisting of catalyst, fraction of polyolefin elastomer and antioxidant was prepared using a roller. All specimens were cured under the same conditions for 4–6 h, per 1 mm in thickness in a water bath operated at 85 °C.

2.3. Measurements

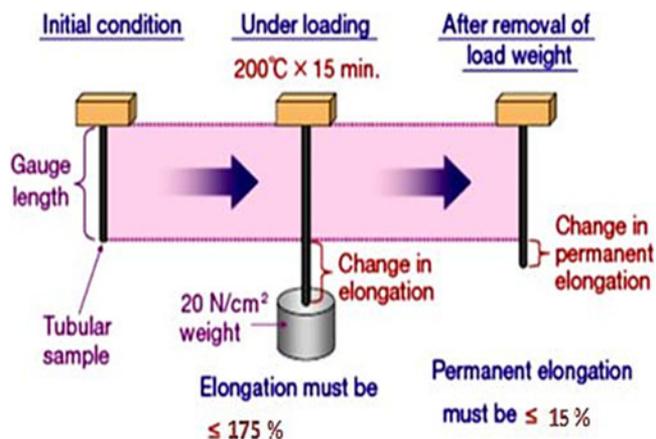
Properties of specimens were determined according to the standard methods presented in Table 1.

2.3.1. Heat aging test

Heat aging test was carried out at 70 °C and 135 °C for 168 h. Dumbbell-shaped specimens (at least 3 for each experiment) were prepared according to the standard presented in Table 1, and stored in a hot air oven with a

Table 1. Test method standards.

Characterization	standard	Test method
Hardness, Shore A	ISO 868: 2003	1 s, 15 s
Tensile strength-at-break and Elongation-at-break	ISO 37: 2011 ISO 527: 2012 ISO 1183: 2012	500 mm min ⁻¹ , 2-kN load cell, MPa
Density	ISO 1183: 2012	–
Melt flow index	ISO 1133: 2005	190 °C /21.6 kg, g/10 min, uncuring
Compression set	ASTM D 395: 2012	22 h at 70 °C 25% initial thickness, %
Tension set	ASTM D 395: 2012	Initial tension was 20%, %
Tear strength	D415149: 2012	kg f/cm
Hot set test	EN 60811-507: 2013	15 minutes, 200 °C, 20 N/cm ² , % 8 h cured at 85 °C
Gel content	ASTM D 2765-95 a: 2016	refluxing xylene containing 1 % of antioxidant for 6 h, %
Heat aging test at 135 °C	IEC 60811: 2013	168 h, 135 °C, %
Heat aging test at 70 °C	ASTM D 573: 2010	168 h, 70 °C, %

**Figure 1.** Schematic design of the hot set test.

natural air flow at temperature 70 °C (compared with rubber compounds) and at 135 °C (a standard for wire and cable). Residual elongation was measured according to IEC 60811: 2013 standard after the exposure time.

2.3.2. Hot set test

The schematic of hot set test is shown in Figure 1. In accordance with EN 60811-507: 2013 standard, the test was conducted such that the tubular test specimen was kept in a high temperature environment (200 °C for 15 min), under a static load (20 N/cm²). The limit of elongation of the specimen was required to be between the gage points ($\leq 175\%$ after 15 min), and also that the limit of permanent elongation between the gage points after removing the load was required to be less than 15%.

3. Results and discussion

3.1. Effect of peroxide initiator

Effect of dicumyl peroxide and benzoyl peroxide on cross-linked compound were compared in Table 2. Effective parameters in the efficiency of silane grafting are include; type and concentration of initiator, solubility of monomer in polymer, processing conditions, silane, catalyst and thermal antioxidant concentration used.^[16,21] Peroxide component not only plays as an initiator of the silane grafting reaction, but also affected as a curing agent. These two roles compete with each other.^[16,22] To the melt grafting

reaction on polyolefins, DCP is known to be an efficient initiator.^[13,16,21,23] In dilute solution, the rate determining of the thermal decomposition of the initiator (peroxide) reaction, follows first order kinetics. Thus, half-lives of the peroxide at different temperatures can be determined from kinetic data. Values of reaction rate constant (k_d), using Arrhenius equation, and half-life ($t_{1/2}$) of DCP and BPO were calculated at various temperatures (160–200 °C).^[21] In this work, the extrusion temperatures were in the range of 170–200 °C or a little less, and the average residence time of the mixtures in the extruder, running at a screw speed of 30 rpm, was about 5 min. Under the studied conditions, BPO has much faster rate of decomposition than DCP, as characterized by their $t_{1/2}$ value. Qi showed that DCP was a more effective initiator than BPO for the grafting maleic anhydride onto acrylonitrile-butadiene-styrene (ABS) at 190 °C.^[21,24] However, contradictory results exist in the literature. For example, Cho carried out the glycidyl methacrylate (GMA) grafting reaction onto PE in an internal mixer at 160 °C and found that under a specific condition, BPO was more effective than DCP.^[21,25] In a work the melt grafting of VTMS onto HDPE using a co-rotating twin-screw extruder, two initiators with different half-lives, i.e. DCP and BPO and different extrusion temperature profiles have been used. The use of a binary initiator mixture would reduce the extreme amount of free radicals generated in the early stages of reactive extrusion, and allow a long lifetime initiator to induce a grafting reaction in the later zones of the extruder. The grafting level depended strongly on the type and concentration of initiator used and extrusion temperature. Using of a binary mixture of BPO/DCP initiator was effectively improved the silane grafting yield, while minimizing the formation of premature gel.^[21] It was found that the rate of crosslinking of the polymer depends strongly on the relative amounts of crystalline and amorphous material.^[23]

The results of our study agree well with that previous work,^[21,25] where the system with BPO initiator shows a higher grafting yield compared to the system using DCP. The melt flow index (MFI) of the silane grafted compound prepared with BOP (0.26 g/10 min) was much lower than that of those prepared with DCP (4.13 g/10 min). As can be seen, the tensile strength of the cross-linked compound prepared using BPO (0.1 w%) after aging (at 135 °C) is higher than that of those prepared using DCP (0.1 w%) (Table 2). The behavior may be mainly due to process conditions

Table 2. Comparison of properties of the cross-linked compounds prepared with DCP and BPO.

properties	0.1 w% BPO	0.1 w% DCP
Hardness (Shore A, 15 s)	79.4	80.0
Hardness (Shore A, 1 s)	82.8	83.2
Tensile strength-at-break	7.8	6.9
ISO 37: 2011		
Elongation-at-break	245	79
ISO 37: 2011		
Tensile strength-at-break	6.0	6.1
ISO 527: 2012		
Elongation-at-break	168	213
ISO 527: 2012		
MFI (190 °C /21.6 kg) uncured	0.26	4.13
Compression set	50.0	28.5
Tear strength	29.5	25.3
Aging Δ tensile , 70 °C	9.0	12.5
Aging Δ Elongation , 70 °C	14.2	47.6
Aging Δ tensile , 135 °C	61.8	67.8
Aging Δ Elongation , 135 °C	37.9	52.1
Density	0.884	0.885
Tensile Modulus, ISO 37: 2011		
20%	3.96	3.51
50%	5.75	5.87
100%	7.01	—
200%	7.80	—
Tensile Modulus, ISO 527: 2012		
20%	3.02	2.66
50%	4.40	3.65
100%	5.80	4.52
200%	—	5.36

(lower actual temperature of the twin-extruder than the amount has set) and the type of polymers used, resulting in higher amount of silane grafted and higher degree of curing by using BPO compared to DCP. However, non of the hardness, density of the cross-linked compound were affected (Table 2). Therefore, further work was focused on BPO as a suitable initiator for grafting of the blend. The reasonable behavior observed for the cross-linked compounds prepared with BPO led to investigate the effect of BPO on the properties of the cross-linked compounds.

3.2. Effect of BPO concentration

Due to the advantages of BPO, the effect of its concentration (0.1–0.3 w%) on the cross-linked compound properties was investigated.

The results are presented in Table 3 and Figures 2–8. The hardness, gel content, tensile strength and density of the cross-linked compounds are not so affected by BPO concentration (Table 3). As regards in a work, the lowest effective initiator for silane grafting, (0.1 w%) have been reported.^[13,21] Also, compounds have been cured for a long time. The reason for slight change in properties can be expressed to the highest cross-linking level. Gel content of the three compounds is not different (Table 3), so it is evident that its effect on the final properties of the compounds are also negligible. However, there are some differences in the properties. It was demonstrated that the maximum values of tear strength (Figure 4), tension set (Figure 5) and tensile modulus (Figures 2 and 3) at a given elongation (Table 3) were obtained for the cross-linked compound with 0.2 w% BPO. In addition, at 0.2 w% BPO, the elongations

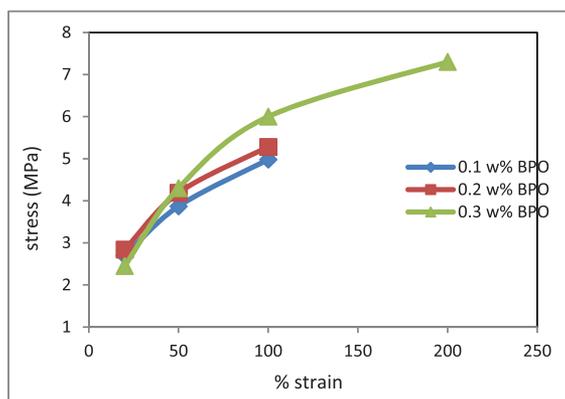
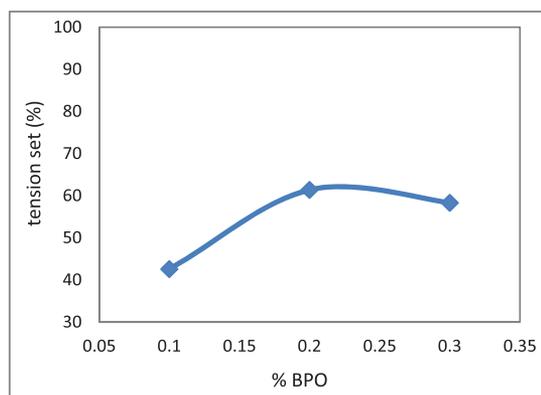
measured by both the ISO standards exhibited minimum values (Table 3). Further work was used the two standard types to study the effect of thickness of the dumbbell-shaped specimens on tensile strength and elongation. The prerequisite for cross-linking is that water molecules to diffuse into wall specimens and reach the cross-linking sites, therefore longer time is required to achieve suitable cross-linking.^[16] In this case, the ISO-37 standard (thickness about 2 mm) is more effective cured than the ISO 527 standard (thickness about 4 mm), and the tensile strength is higher (Table 3). With increasing BPO, the tension set was initially increased and then reached the limit value (60%) (Figure 5). The aging performance was not affected by increasing BPO concentration, however, it was increased in some cases (Figures 6 and 7). This indicates that the highest cross-linking level is possibly achieved, as reported.^[21] Finally, according to the properties achieved, BPO (0.2 w%) was selected as the optimum value for further studies.

3.3. Effect of antioxidant

The effect of Irganox 1010 concentration (0.0–0.5 w%) on the thermal stability of the cross-linked compound was investigated. It is obvious that the addition of the antioxidant could increase the thermal stability of the cross-linked compound. The increase of antioxidant content (up to 0.5 w%) linearly increased the length of time in which the cross-linked compound resists to oxidation (Figure 8). By the addition of the antioxidant (0.3 w%), the curing time required to confirm the hot set test was reduced of from 16 h to 8 h, however, the tension set was decreased by about 15% (Table 4). During the silane grafting reactions, the

Table 3. Effect of BPO concentration on properties of different the crosslinked compounds.

properties	0.1 w% BPO	0.2 w% BPO	0.3 w% BPO	Confidence interval
Hardness (Shore A, 15 s)	80.4	80.5	80.9	80.5 ± 0.4
Hardness (Shore A, 1 s)	83.1	84.0	83.6	83.5 ± 0.5
Tensile strength-at-break ISO 37: 2011	7.4	7.4	7.8	7.6 ± 0.2
Elongation-at-break ISO 37: 2011	397	277	385	–
Tensile strength-at-break ISO 527: 2012	5.9	6.0	6.1	6.0 ± 0.1
Elongation-at-break ISO 527: 2012	198	168	213	–
Gel content %	71	79	71	75 ± 4
Compression set	53.0	40.4	50.0	–
Tension set	42.6	61.4	58.3	–
Tear strength	20.7	22.6	20.7	21.0 ± 1.0
Aging Δ tensile , 70 °C	5.4	3.8	0.4	–
Aging Δ Elongation , 70 °C	36.1	52.9	12.8	–
Aging Δ tensile , 135 °C	59.4	59.3	1.0	–
Aging Δ Elongation , 135 °C	49.0	45.9	47.7	–
Density	0.886	0.886	0.885	0.886 ± 0.001
Tensile Modulus, ISO 37: 2011				
20%	1.45	1.45	1.32	–
50%	2.83	3.89	2.76	–
100%	3.95	4.93	4.11	–
200%	5.61	6.86	5.90	–
300%	6.54	–	6.90	–
400%	–	–	7.69	–
Tensile Modulus, ISO 527: 2012				
20%	2.70	2.84	2.45	–
50%	3.87	4.19	3.51	–
100%	4.98	5.28	5.88	–

**Figure 2.** Effect of BPO concentration on the tensile modulus (ISO 37: 2011) of the cross-linked compounds.**Figure 3.** Effect of BPO concentration on the tension set (ISO 527: 2012) of the cross-linked compounds.

formation of radical alkyl in macromolecules is suppressed by the antioxidants present in reaction medium, where the products of the peroxide decomposition react with the antioxidant in a non-useful reaction. Therefore, the decomposed peroxide has to be compensated by excess peroxide otherwise the silane grafting efficiency would be lost.^[16,26]

The grafting process limits the choice of antioxidant, since many of them are effective radical scavengers and can inhibit the grafting reaction. Tiolyl antioxidants can not be used because they are chemically and mechanically bonded to the polymer during the process. Preferably the phenolic antioxidant contains no sulfur atom are use.^[16,22,27] As

incorporation of antioxidant would be inevitable to prevent the product from degradation,^[21] a possible practical method to reach a desirable grafting extent as well as the least thermal degradation, is to incorporate a part of a predetermined amount of suitable antioxidant within the process and the remainder to be mixed in the catalyst master batch. This has been done before addition of any other additives (such as carbon black) which otherwise would interfere with the silane grafting reactions. An alternative is to take advantage of higher amounts of peroxide which associates with some scorch occurring during the grafting stage, causing a rough surface in the final product due to resulted gelled spots.^[16]

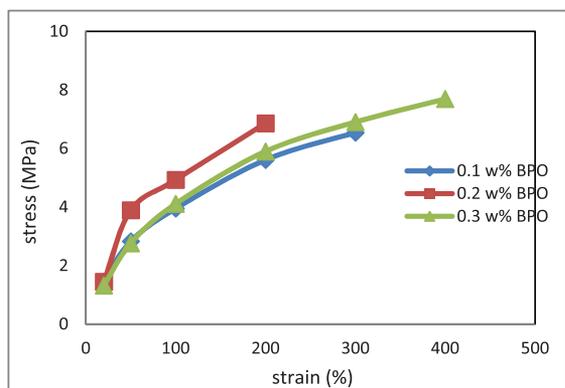


Figure 4. Effect of BPO concentration on tear strength of the crosslinked compounds.

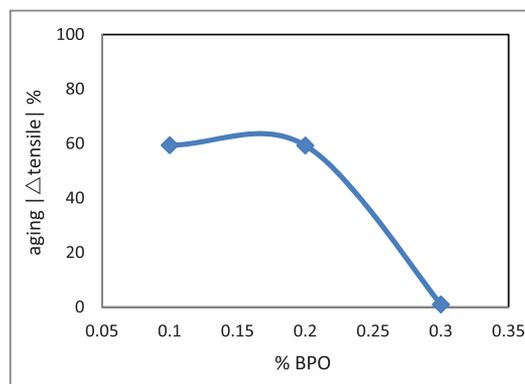


Figure 7. Effect of BPO concentration on aging |Δtensile| % (168 h, 135 °C) of the crosslinked compounds.

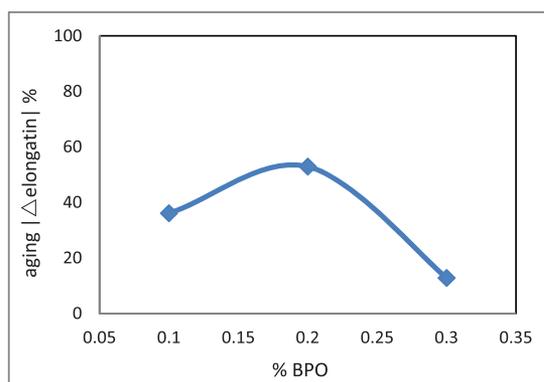


Figure 5. Effect of BPO concentration on tension set of the cross-linked compounds.

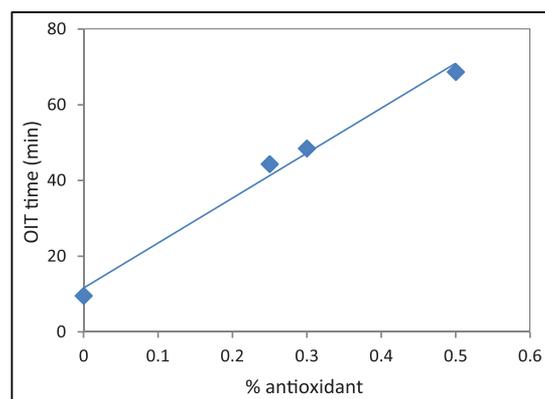


Figure 8. Effect of antioxidant (Irganox 1010) concentration on the crosslinked compound sustainability at 210 °C.

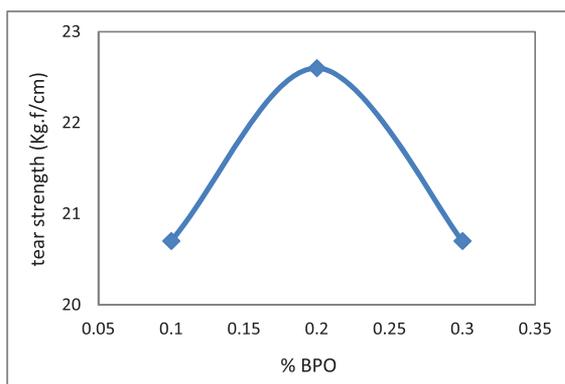


Figure 6. Effect of BPO concentration on aging |Δelongation| % (168 h, 70 °C) of the crosslinked compounds.

3.4. Effect of DBTDL catalyst on MFI

The aim of this part of the study was to select an appropriate method between the Monosil method and Sioplas method. Here, silane grafted compound was prepared without using catalyst, and also it was not cured. The effect of DBTDL on the MFI of silane grafted compound (Figures 9). The MFI of the silane grafted compound (8.2 g/10 min) decreased with aging (room temperature aging) and reached a limited value (6.4 ± 0.1 g/10 min) using Sioplas method. While, the MFI of silane grafted compound greatly

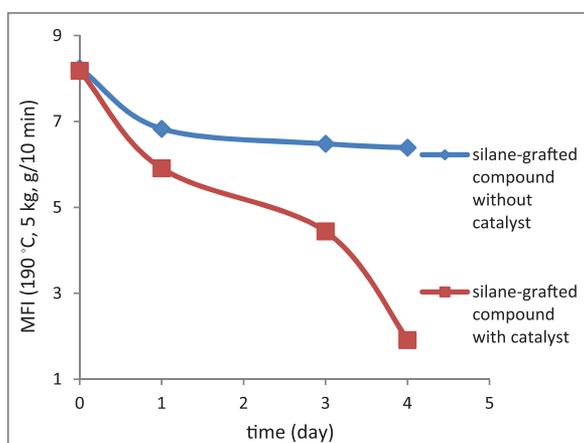
decreased (1.9 g/10 min) in the presence catalyst (0.035 w%) using the Monosil method (Figure 10) which is not a desirable feature. Therefore, we chose the two-step Sioplas process because it caused lower crosslinking degree as well as minimum premature crosslinking, which, in turn, prevented the formation of gell spots and rough surface.^[16] The Sioplas process, however, produced a smooth surface in the presence of DBTDL which was added at the second step of the method.

4. Conclusion

Silane moisture cross-linking of POE/LLDPE blend was carried out using the single-step Monosil and two-step Sioplas processes. The silane grafting process was conducted in an industrial scale twin-screw extruder. Between two peroxides, BPO and DCP, the BPO was chosen as suitable initiator and adapted to use in the process conditions. The mechanical properties of cross-linked compounds such as hardness, density and tensile strength were not significantly affected by BPO concentration. However, for the cross-linked compounds containing 0.2 w% BPO, the optimum values of 40.4%, 79% and 22.6% were, respectively, obtained for the compression set, gel content and tear strength. Since the Monosil process was sensitive to the formulation of compound, the Sioplas process was chosen. The curing time

Table 4. Effect of antioxidant (0.3 w%) on various properties of the cross-linked compound.

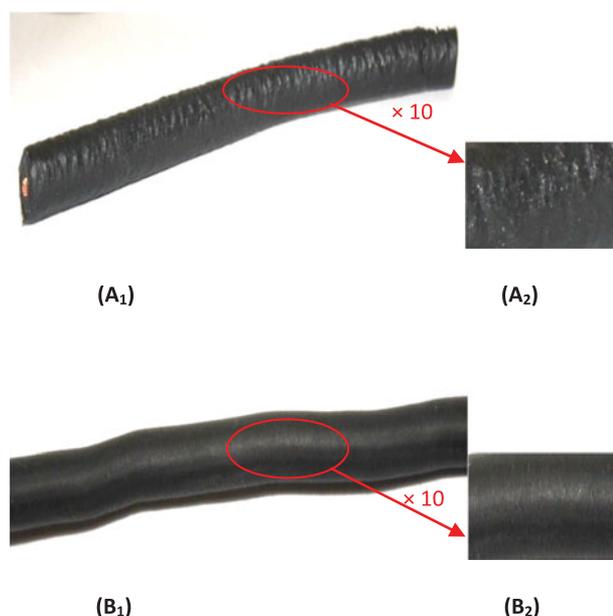
properties	0 w% antioxidant	0.3 w% antioxidant	
Hot set (8 h cured at 85 °C)	No passed	Extension >175%	Set >15% –23
Hardness (Shore A, 15 s)	80.5	80.3	
Hardness (Shore A, 1 s)	84.0	82.6	
Tensile strength-at-break ISO 37: 2011	7.2	7.8	
Elongation-at-break ISO 37: 2011	272	208	
Tensile strength-at-break ISO 527: 2012	5.9	6.0	
Elongation-at-break ISO 527: 2012	168	196	
Gel content %	79	77	
Tension set	61.4	46.8	
Tear strength	22.6	22.1	
Aging Δ tensile , 70 °C	3.80	0.98	
Aging Δ Elongation , 70 °C	52.9	62.8	
Density	0.886	0.886	
Tensile Modulus, ISO 37: 2011			
20%	1.45	2.10	
50%	3.89	4.30	
100%	4.93	6.00	
200%	6.86	7.30	
Tensile Modulus, ISO 527: 2012			
20%	2.84	3.90 4.80	
50%	4.19		
100%	5.28	5.86	

**Figure 9.** Effect of room temperature aging on the MFI of silane grafted compound with and without catalyst.

required for confirming hot set test was decreased from 14 to 16 h to 8 h by the addition of pentaerythritol tetrakis (3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate) antioxidant (0.3 w%). The gel content, tensile strength and density of the cross-linked compound, however, were not affected in the presence of the antioxidant. Also, the OIT time increased linearly with increasing the antioxidant concentration (up to 0.5 w%). we chose the two-step Sioplas process because it caused lower cross-linking degree as well as minimum premature cross-linking, which, in turn, prevented the formation of gell spots and rough surface.

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**Figure 10.** Effect of pre-crosslinking of silane grafted compound on the product appearance. Monosil process (A₁ and A₂ (and Sioplas process (B₁ and B₂). A₁ and B₁ have a resolution of 5184 × 1114 pixels; A₂ and B₂ have a resolution of 295 × 181 pixels.

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