Rheological Behavior of Chlorosulfonated Polyethylene Composites: Effect of Filler and Plasticizer

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ABSTRACT: The rheological properties of chlorosulfonated polyethylene (CSM) loaded with conductive carbon black filler were measured using capillary rheometer at three different temperatures (110, 120, and 130°C) and four different shear rates (12.26, 24.52, 61.3, and 122.6 s^{-1}). The effect of filler and plasticizer [dioctyl phthalate (DOP)] loading on melt flow properties of CSM was also studied. The viscosities of all samples decrease with shear rate indicating their pseudoplastic or shear thinning nature. The higher shear viscosity is observed for the CSM loaded with higher filler content, which may be due to inhibition of the polymer chain motion by the filler particles. With increasing filler loading the extrudate swell clearly decreased, which is attributed to the limitation of the elastic recovery of the polymer chains by filler particulates. Further, the reduction in die-swell ratio with increase in plasticizer loading indicates a reduction in melt elasticity compared with the composite containing no DOP. The dependence of shear viscosity on temperature obeyed the Arrhenius–Eyring expression, and the activation energy (E_γ) decreased with increasing shear rate. Extrudate swell is a non-linear function of shear rate. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 000: 000–000, 2012

Key words: activation energy; carbon black; filler; rheology; viscosity

INTRODUCTION

Fillers have a significant effect on the properties like mechanical, dynamic mechanical, and in general on the overall performance of polymer composites. The incorporation of the fillers into a rubber is of significant commercial importance, as fillers not only enhances the mechanical properties of the final products but also decreases the cost of the end product. The knowledge of rheological properties of elastomers is of considerable importance in predicting and comprehending their processing characteristics. Both the viscous and elastic properties of elastomer can be analyzed and correlated with the flow behavior. The viscous flow is related to the output rate, whereas the elastic behavior corresponds to the dimensional stability.

Einhorn and Turetzky[1] have shown the use of capillary rheometer to characterize elastomeric flow of carbon black-filled styrene–butadiene rubber (SBR) systems. True shear stresses at corresponding true shear rates were considerably higher for the carbon black-filled SBR compound than that of the virgin elastomers; however, the addition of black reduces the extent of deviation from Newtonian behavior. Effect of fillers like carbon black and silica on the melt flow properties of unfilled and filled brominated isobutylene-co-paramethylstyrene has been reported by Kumar et al.[2] wherein the silica filled system showed higher activation energy than the carbon black-filled systems. Rheological properties of self-vulcanizable rubber blends based on chlorosulfonated polyethylene (CSM) and carboxylated nitrile rubber filled with carbon black were studied by Mukhopadhyay and Gupta.[3] It was reported that the addition of carbon black to the blends decreased the die swell value and surface roughness of the extrudates significantly. The processing behavior of acrylonitrile butadiene rubber and high styrene resin (HSR) blend filled with carbon black and aluminium silicate were studied by Nayak and Tripathy.[4] In this study decrease in activation energy for the melt flow process with an increasing shear rate and an increasing wt % of HSR was observed. Melt rheology of phosphorylated cashew nut shell liquid prepolymer (PCNSL) modified ethylene propylene diene monomer (EPDM) rubber has been studied by Menon et al.[5] The plasticizing effect of PCNSL in EPDM was evident from the progressive decrease in melt viscosity, consistency index, shear modulus and activation energy of melt flow with increase in dosage of PCNSL. Effect of curing agent and temperature in conductive carbon black (Vulcan XC 72) filled EPDM rubber was reported recently by Mahapatra and Tripathy.[6] In case of Vulcan XC 72 filled compound die swell

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TABLE I
Compositions of Unfilled and Ensaco 350G filled CSM Composites in phr (Parts Per Hundred Rubber)

Mix designation	CSM	Ensaco 350G	DOP
G_0	100	0	0
HB_1	100	10	0
HB_2	100	20	0
HB_3	100	30	0
HB_4	100	40	0
HB_{31}	100	30	3
HB_{32}	100	30	5
HG_{33}	100	30	10
HB_{34}	100	30	15

increases with increase in curing agent content and temperature compared with the base compound.

Though some literature in the area of blends of CSM has been reported recently, they deal with physico-mechanical studies only.[7–12] But no work on only CSM rubber compound have been reported even though it possesses good weather resistance, good electrical resistance, and good ageing resistance. CSM is commonly used as cable sheath material in nuclear environment, industrial roller and as industrial hose etc for which rheological studies is an important aspect. Therefore, present investigation was carried out to study the rheological properties of conductive carbon black-filled CSM compound based on its industrial relevance.

In the present communication, the results of the investigations of rheological behavior of Ensaco 350G reinforced CSM composites are reported using a Monsanto Processability Tester, a capillary viscometer with special reference to (a) effect of filler loading [10, 20, 30, and 40 phr] (b) plasticizer [dioctyl phthalate (DOP) at 3, 5, 10, and 15 phr loading, with 30 phr of carbon black loading in each case]. The melt flow characteristics such as viscosity, pseudoplasticity index, activation energy of melt flow and the parameters indicating elasticity like die-swell ratio have been calculated and reported in this article.

2. EXPERIMENTAL

Materials

The following materials were used in preparation of compound. CSM rubber [(Hypalon-40), 35% chlorine content, Mooney viscosity ML_{1+4} at 100°C = 56] manufactured by Dupont Dow Elastomers was used. The conductive filler used in this study was highly conductive carbon black, Ensaco 350G having a BET Nitrogen surface area 770 m^2/g, pH-8, manufactured by Timcal Corporation, Belgium. The plasticizer used was DOP, pharmaceutical grade processing oil with B.P 340°C supplied by C.D. Pharmaceuticals Calcutta, India.

Sample preparation

Details of the formulations of the compounds are given in Table I. The mixing of rubber and all other ingredients were carried out in a two roll mixing mill (325 mm × 150 mm) at a friction ratio of 1:1.19 according to ASTM D 3182 standards at room temperature with optimized nip gap, mixing time, and uniform cutting operation.

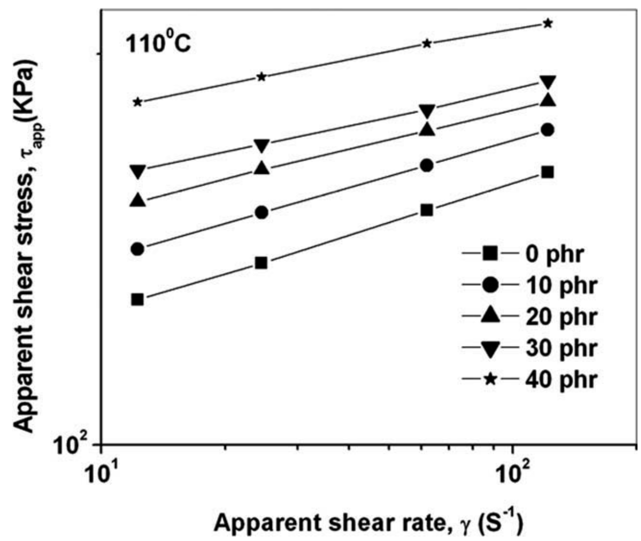

Figure 1 Apparent shear stress of carbon black-filled CSM composites as a function of apparent shear rate at varying filler concentrations.

Measurement of rheological properties

The melt flow properties of the gum CSM (without filler), the conductive carbon black reinforced CSM composites and the plasticized carbon black filler loaded CSM composites were measured by means of a fully automated capillary viscometer (Monsanto processibility tester with barrel radius = 9.53 mm).

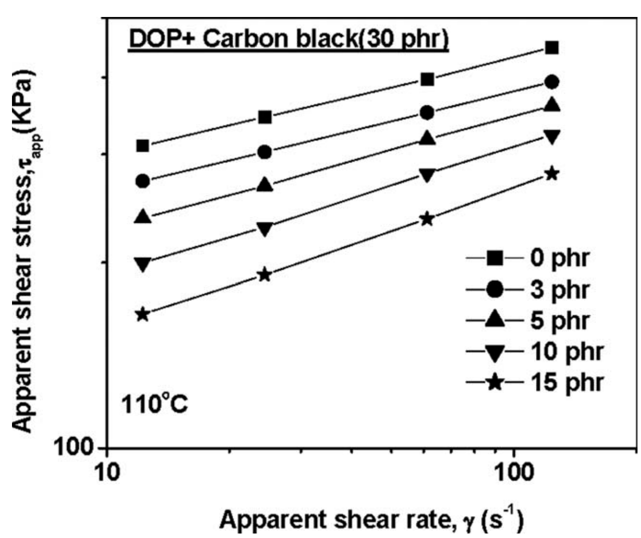

Figure 2 Apparent shear stress of carbon black-filled CSM composites as a function of apparent shear rate at varying DOP loadings.

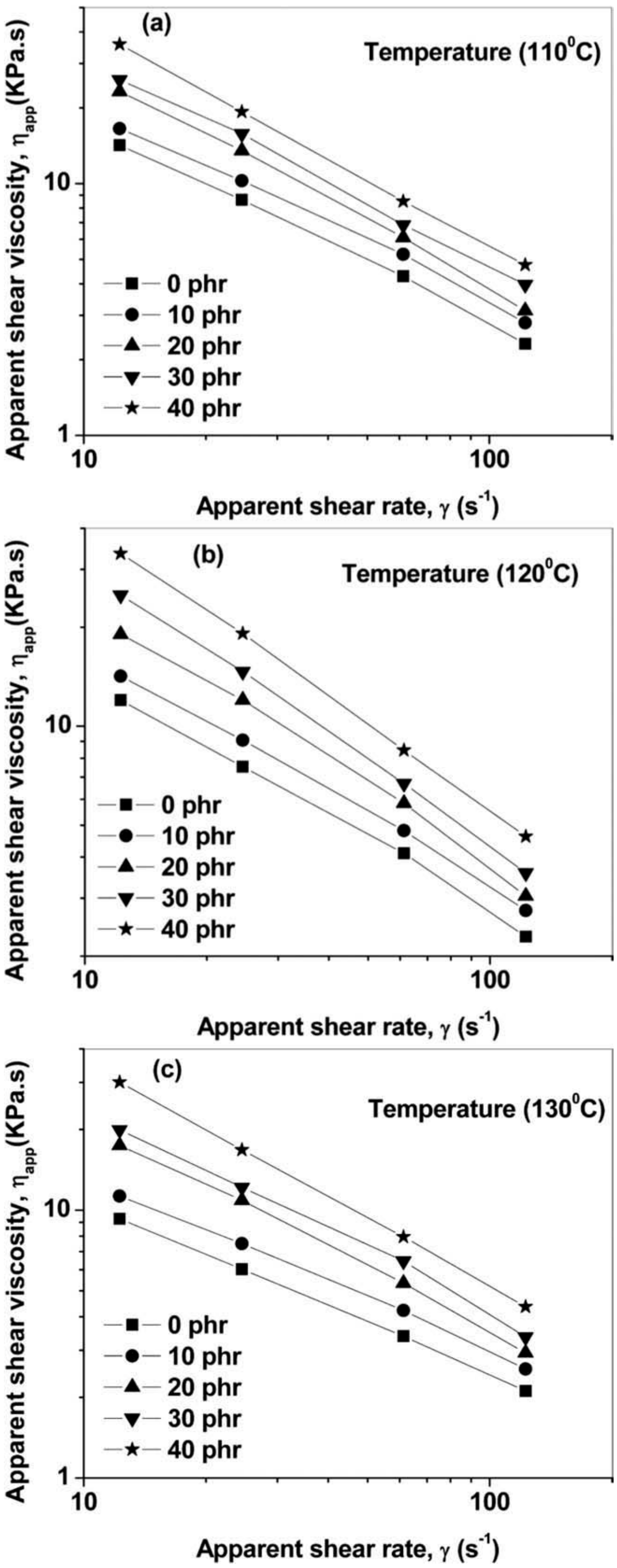

Figure 3 Apparent shear viscosity of carbon black-filled CSM composites as a function of apparent shear rate at various filler loadings at (a) 110, (b) 120, and (c) 130°C.

The entire barrel and the capillary assembly are electrically heated with a microprocessor based temperature controller. The capillary used having a length to diameter ratio equal to 30 (length 30.00 mm; diameter 1.00 mm). The compound entrance angles of capillary were 45 and 60°C, which are known to minimize the pressure drop at entrance. Therefore, the Bagley correction can be assumed to be negligible and the apparent shear stress can be taken as equal to the true shear stress.[13] The preheated time for each sample was 5 min. The extrusion studies were carried out at three different temperatures (110, 120, and 130°C) and at four different shear rates (12.26, 24.52, 61.3, and 122.6 s^{-1}). The rate of shear variation was achieved by changing the speed of the plunger automatically. The pressure at the entrance of the capillary was recorded automatically with the help of pressure transducer. The apparent shear stress (τ_{app}), apparent shear rate (γ_{app}) and apparent shear viscosity (η_{app}) were calculated using the following equations[14]

$$\tau_{app} = d_c \Delta p / 4 l_c \tag{1}$$

$$\gamma_{app} = 32Q / \pi d_c^{3'} \tag{2}$$

$$\eta_{app} = \tau_{app} / \gamma_{app'} \tag{3}$$

where ΔP is the pressure drop across the length of the capillary; d_c and l_c are diameter and length of capillary, respectively; and Q, the volumetric flow rate of the material.

The flow behavior index, η and consistency index, k were calculated by using the Power Law model

$$\tau_{app} = k\gamma_{app^n} \tag{4}$$

By definition $\eta_{app} = \tau_{app}/\gamma_{app}$, therefore

$$\eta_{app} = k\gamma_{app^{n-1}} \tag{5}$$

Logarithmic form for eq. (5) may be written as

$$\log\eta_{app} = \log k + (n-1)\log\gamma_{app} \tag{6}$$

TABLE II
Flow Behavior Index, *n* and Consistency Index *k* (KPa s^n) for Conductive Carbon Black Loaded CSM Composites

	110°C		120°C		130°C	
Mix designation	*n*	*k*	*n*	*k*	*n*	*k*
G_0	0.14	0.30	0.17	0.27	0.19	0.22
HB_1	0.16	0.31	0.18	0.28	0.21	0.24
HB_2	0.16	0.36	0.19	0.33	0.24	0.32
HB_3	0.17	0.36	0.19	0.35	0.24	0.33
HB_4	0.18	0.39	0.20	0.39	0.26	0.37

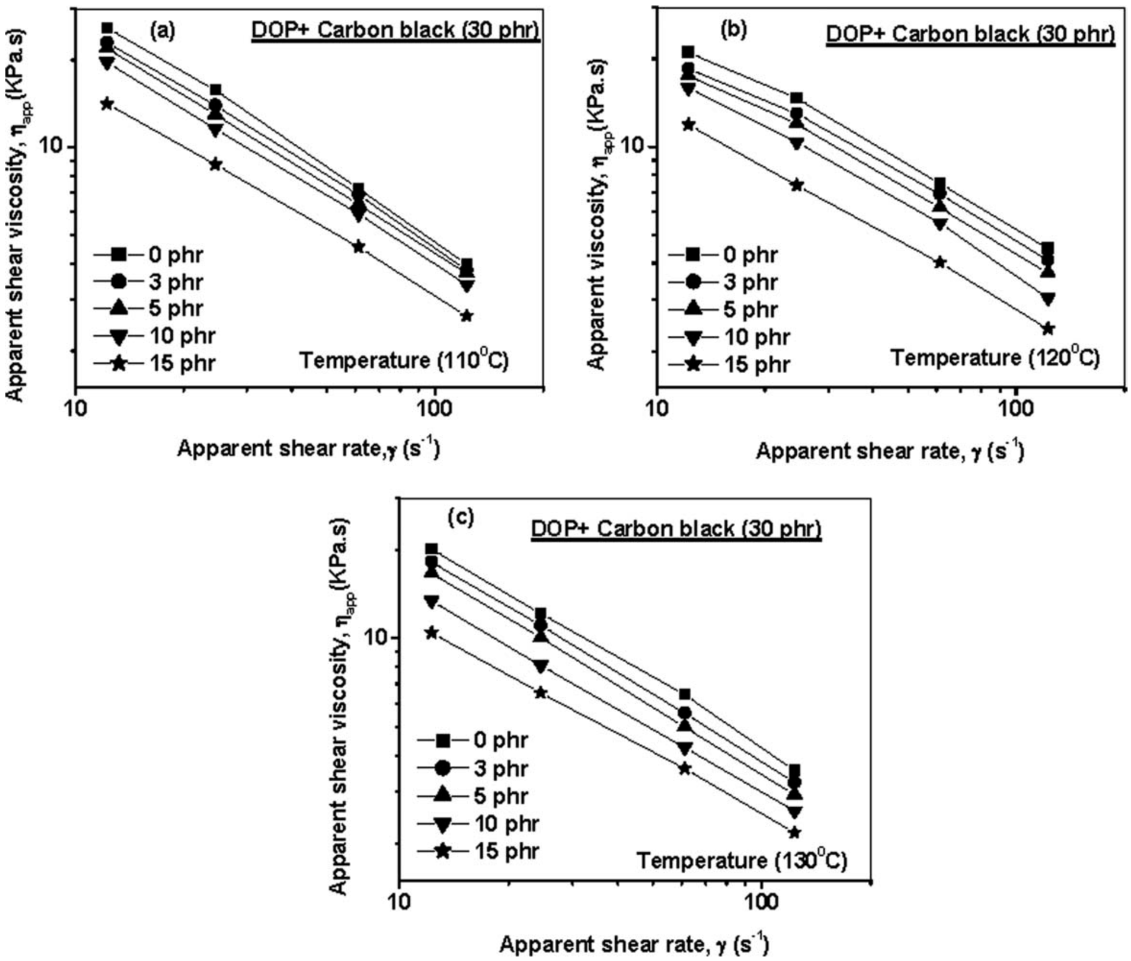

Figure 4 Apparent shear viscosity of carbon black filled CSM composites as a function of apparent shear rate at various DOP loadings at (a) 110, (b) 120, and (c) 130°C.

The values *n* and *k*; were calculated from the linear plot of apparent viscosity vs. apparent shear rate.

Activation energy of melt flow

Activation energy of viscous flow was derived from the Arrhenious–Frenkel–Eyring equation,[15] which is valid for the power law of fluids, as follows:

$$\eta_{app} = Be^{E\gamma/RT} \tag{7}$$

where, E_γ is the activation energy of the flow at a particular shear rate, *R*, the gas constant, *T*, the temperature in Kelvin, *B*, the pre-exponential component and η_{app}, the viscosity in KPa.s at that shear rate. For different systems, from the slope of the linear plot of log viscosity vs. reciprocal of temperature ($1/T$), the value of E_γ/R was obtained from which the activation energy was calculated.

Scanning electron microscopy (SEM)

The surface morphology of the composites was studied by using a JEOL JSM- 800 scanning electron microscope operating at an accelerating voltage of 25 kV at 35× magnification. The samples were sputter coated with gold.

RESULTS AND DISCUSSION

Flow properties

Figure 1 shows the logarithmic plots of the apparent shear stress vs. apparent shear rate of unfilled and conductive carbon black-filled systems at 110°C for various filler concentrations. Plots corresponding to other temperatures follow the similar trends. The apparent shear stress of both unfilled and Ensaco 350G-filled CSM composites exhibit approximately a linear increase with increasing apparent shear rate, which indicate that the melts for all samples obey the power law[16] over the entire range of shear rate studied. With an increase in filler concentration, the shear stress increases. The effect of plasticizer loading was studied with addition of DOP for the system containing 30 phr of conductive carbon black. It was observed that the shear stress of the systems decreased with the addition of DOP (Fig. 2). It can

TABLE III
Flow Behavior Index, *n* and Consistency Index *k* (KPa s^n) for Conductive Carbon Black Loaded CSM Composites (Effect of DOP Content)

	110°C		120°C		130°C	
Mix designation	*n*	*k*	*n*	*k*	*n*	*K*
HB_3	0.17	0.36	0.19	0.35	0.24	0.33
HB_{31}	0.21	0.34	0.25	0.32	0.26	0.31
HB_{32}	0.21	0.34	0.26	0.31	0.26	0.3
HB_{33}	0.23	0.32	0.26	0.3	0.28	0.29
HB_{34}	0.27	0.29	0.3	0.26	0.33	0.24

be explained on the basis of plasticization effect, which results in reduction of melt elasticity. Mobility of the polymer chain segments increases with increase in dosage of DOP, which in turn increases flow properties. The DOP-filled CSM composites also obeyed the power law over the entire range of shear rate studied.

Figure 3 illustrates the dependence of apparent shear viscosity on the apparent shear rate of both unfilled and Ensaco 350G-filled CSM composites at three different temperatures (110, 120, and 130°C). The viscosity decreases with the shear rate showing the pseudoplastic or shear thinning nature of all the systems studied. Both the gum CSM and its filled compounds follow the power law model. Generally speaking, pseudoplastic behavior can arise in either of two ways.[17] In one case, asymmetric molecular chains are extensively entangled and/or randomly oriented at rest. The molecular chains become oriented and the numbers of entanglements are reduced under applied shear, which results in the decrease in viscosity. At very high shear rate, the orientation may be complete, and near-Newtonian behavior may be observed. In the other case, highly solvated molecular chains may be present. With increasing shear rate, the solvated layers may be sheared away, resulting in decreased viscosity.[18] The viscosity of the gum CSM is lower than that of the filled systems at all the temperatures studied. The increase in viscosity with loading of carbon black can again be explained by the hydrodynamic effect of the fillers.[19] At higher filler loadings, the reduction in the volume fraction of the flow medium would be higher, resulting in greater restriction on the flow.

The temperature sensitivity is more pronounced at lower shear rates due to the fact that high shear rates lead to a decrease of the entanglement density of the polymer chains and this decrease is likely to occur independently of the diffusive motion of the chains.[18]

The consistency index (*k*) and flow behavior index (*n*) for the gum and filled CSM composites are given in Table II. It is quite obvious that consistency index,

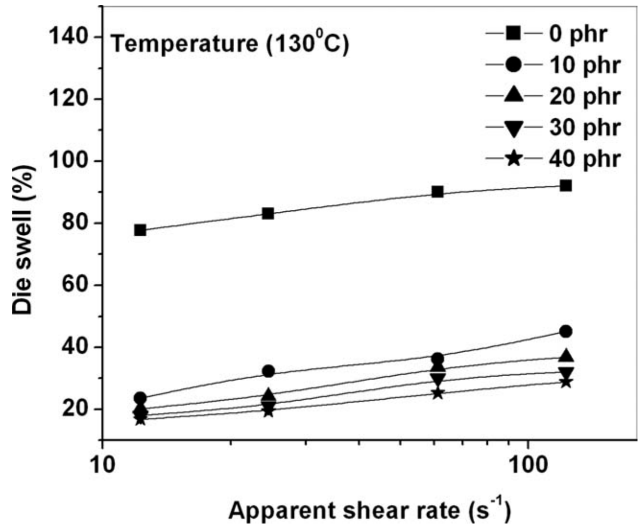

Figure 5 Die swell (%) of unfilled and carbon black-filled CSM composites as a function of apparent shear rates.

k is more for the filled elastomer compared with the gum rubber. The *k* value increases with increase in filler loading indicating the increase in resistance to flow. The *k* value decreases with increase in temperature resulting in decrease in resistance to flow for the gum and the filled systems. Decrease in resistance to flow with increase in temperature may be due to accelerated molecular motion due to the availability of greater free volume, the decrease of entanglement density and weak intermolecular interactions. The variation in *n* value shows the pseudoplastic behavior of these CSM systems. The value of *n* also increases with increase in filler loading, indicating a decrease in the pseudoplastic behavior (Table II). The pseudoplasticity of a system is a

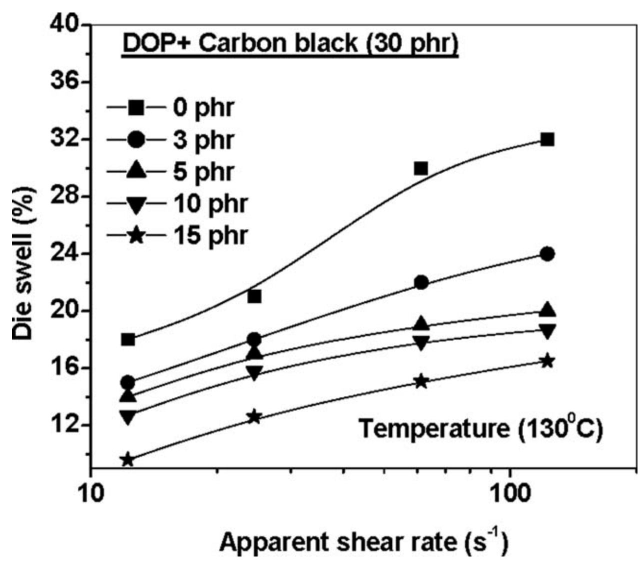

Figure 6 Die swell (%) of carbon black filled CSM composites as a function of apparent shear rates: effect of DOP loadings.

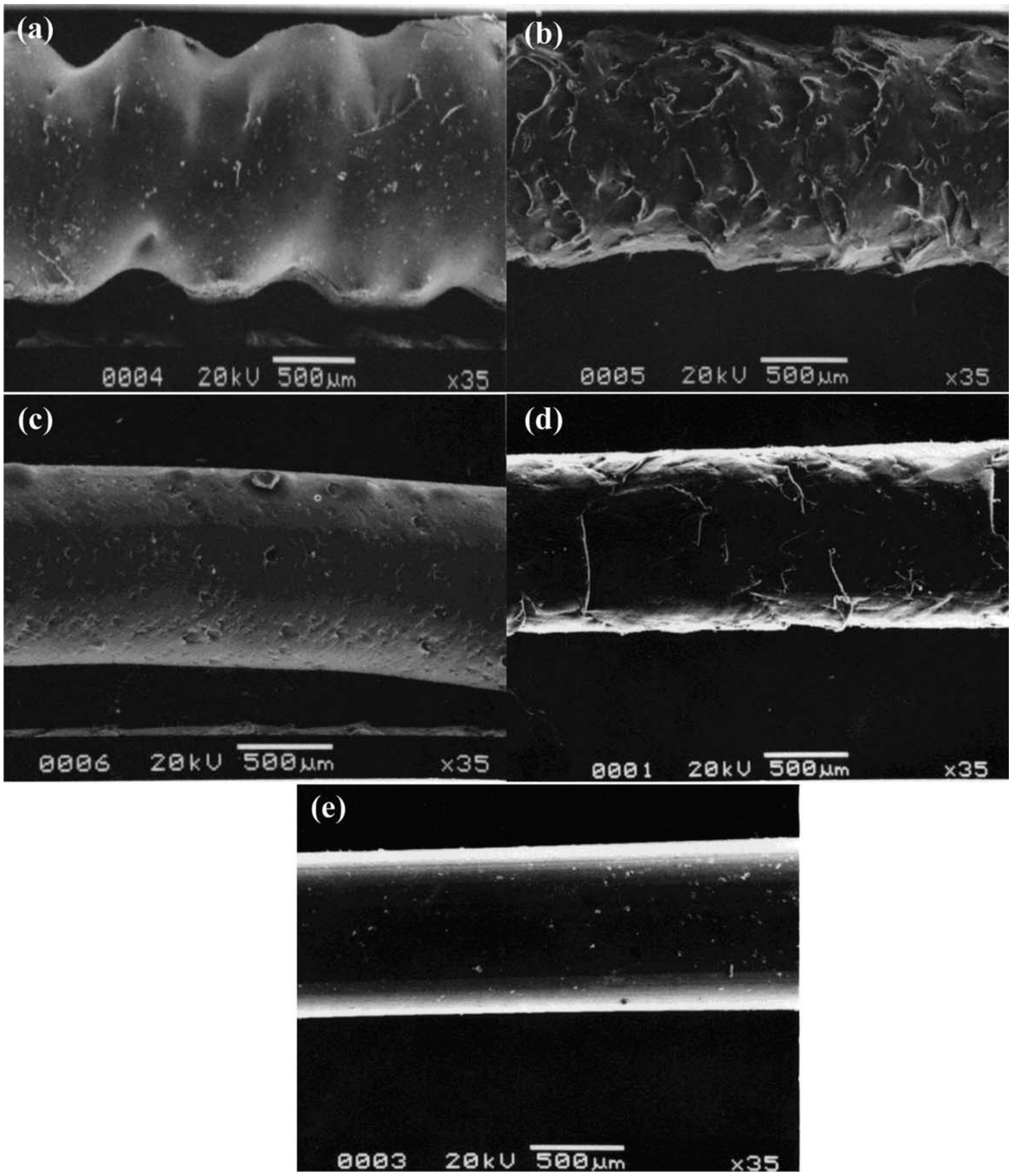

Figure 7 SEM micrographs of the extrudates obtained at shear rate of 112.6 s^{-1} and temperature of 110°C: (a) unfilled, (b) 10, (c) 20, (d) 30, and (e) 40 phr.

consequence of the capacity of the polymer molecule to orient them in the direction of flow. In the case of high-structure carbon black, carbon black particles are joined into long chains and clusters of three-dimensional aggregates. Higher the structure of the carbon black, the more irregular is the shapes of the aggregates. The occlusion of polymer within the filler aggregates enhances the effective hydrodynamic volume of the filler. High-structure carbon black particles not only have higher anisometry but also have higher occlusion of polymer chains within the aggregates. As the filler loading increases, a larger number of polymer chains get absorbed on the filler surface. This decreases the tendency toward molecular orientation, thus decreasing the pseudoplastic behavior.[20] For other filled systems, it is also observed that n increases and k decreases with increase in temperature, indicating a decrease in pseudoplastic behavior and the resistance to flow.[2,13]

Figure 4 illustrates the dependence of apparent shear viscosity on the apparent shear rate with different DOP loadings in the system containing 30 phr of conductive carbon black at three different temperatures (110, 120, and 130°C). The viscosity of all

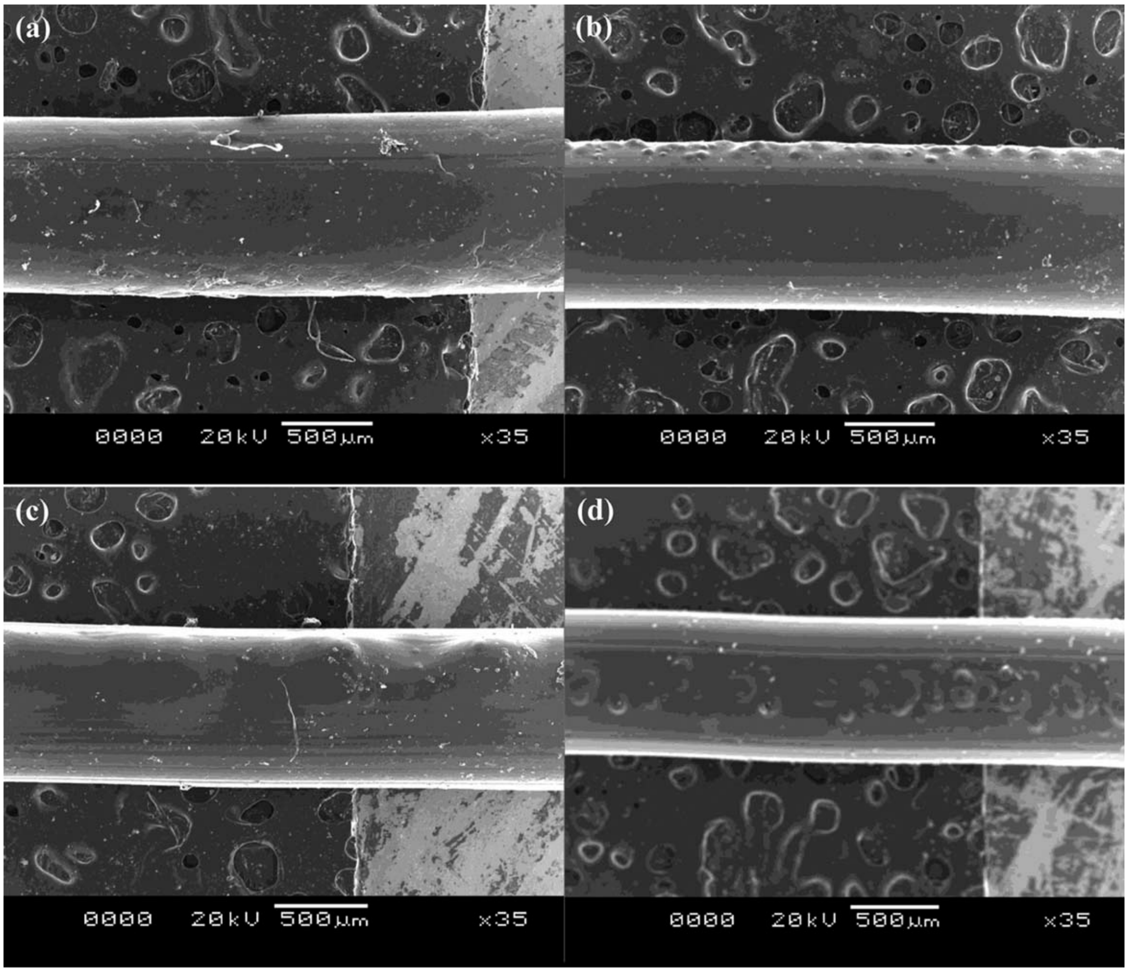

Figure 8 SEM micrographs of the extrudates obtained at shear rate of 112.6 s^{-1} and temperature of 110°C: effect of DOP loadings. (a) 3, (b) 5,(c) 10, and (d) 15 phr.

composites reduces with increase in shear rate due to the shear thinning or pseudoplastic behavior. Figure 4 shows that at any particular rate of shear and temperature, the DOP-filled CSM composites has lower viscosity than filled CSM composites with no plasticizer content. This can be explained in the terms of the hydrodynamic effect of the oil, which increases the volume fraction of the flow medium and tends to lower the viscosity of the system.[2] Figure 4 shows that an increase in dosage of DOP from 10 to 15 phr in 30 phr carbon black-loaded CSM composites results in progressively greater decrease in viscosity at the different shear rates and temperatures as compared with the unmodified CSM. When DOP is added to the polymer matrix, the polymer chain mobility is less hindered due to better filler dispersion, which in turn decreases the shear viscosity.

With increase in temperature the viscosity decreases. It can be explained in the same way as in case of CSM composites with different filler loadings. The consistency index, k and flow behavior

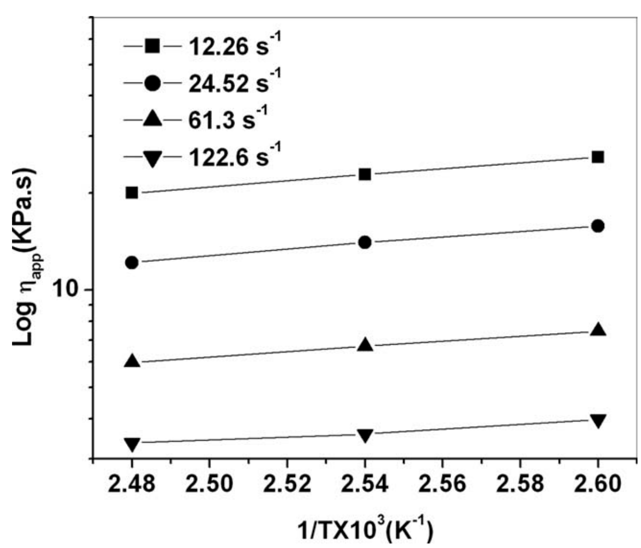

Figure 9 Apparent shear viscosity of 30 phr carbon black-loaded CSM composites as a function of reciprocal temperatures ($1/T$) at various shear rates.

TABLE IV
Calculated Values of Activation Energy (KJ/mol) and Standard Deviation of Carbon Black-Filled CSM Composites at Different Shear Rates

	Shear rate (s^{-1})							
	12.26		24.52		61.3		122.6	
Mix designation	Eγ	SD	Eγ	SD	Eγ	SD	Eγ	SD
G_0	12.8	4.41×10^{-3}	10.8	1.91×10^{-3}	7.64	2.19×10^{-3}	5.07	0.14×10^{-3}
HB_1	11.47	1.31×10^{-3}	10.6	5.43×10^{-3}	7.06	1.24×10^{-3}	3.74	0.28×10^{-3}
HB_2	7.81	6.22×10^{-3}	7.73	3.27×10^{-3}	6.06	4.7×10^{-3}	3.65	2×10^{-3}
HB_3	5.98	1.43×10^{-3}	5.65	5.24×10^{-3}	4.9	1.31×10^{-3}	2.9	6.52×10^{-3}
HB_4	5.98	5.04×10^{-3}	5.57	1.91×10^{-3}	4.24	4.42×10^{-3}	1.9	1.04×10^{-3}

index, n for the both filled (30 phr) and DOP-filled CSM composites at three different temperatures (110, 120, and 130°C) are given in Table III. The results show a progressive increase in the flow behavior index with increase in dosage of DOP from 3 to 15 phr and with increase in temperature from 110 to 130°C. Thus, the system becomes less shear thinning as temperature and dose of DOP are increased. In other words, increase in the flow behavior index of the DOP modified CSM composites is expected to result in better distribution of shear rate in the bulk of the polymer melt leading to better mixing.

With increase in temperature from 110 to 130°C a decrease in the constituency index has been observed. The relatively lower values of the constituency index of plasticized CSM composites reflect its lower melt-viscosity, which may in turn facilitate a faster extrusion.[21] On increasing the dosage of DOP (from 0 to 3 to 15 phr), the consistency index, k decreases smoothly. It may be due to a considerable decrease in viscosity and shear stress acting on the system with increase in plasticizer concentration.

Extrudate swell

Extrudate swell varies with shear rate, temperature, die length, and filler type.[22] Figure 5 illustrates the dependence of extrudate swell on apparent shear rate and filler concentrations at 130°C. Similar trends are also observed for 110 and 120°C. Extrudate swell of all materials increase with an increase in apparent shear rate in a nonlinear relationship. At the lower apparent shear rate, extrudate swell increases gradually, increase being relatively more at higher apparent shear rates. At higher shear rates, the recoverable elastic energy stored in the polymer melt flow increases, which results in an increase of extrudate swell.[23] Extrudate swell occurs due to the recovery of elastic deformation imposed in the capillary. The presence of filler can increase energy dissipation of the system by movement of the filler, which may be easier than that of the polymeric chains for a given shear rate.[24] Hence, the elasticity recovery, and consequently the extrudate swell of a filled polymer is less than that of the unfilled material.

Figure 5 clearly shows that the extrudate swell of the conductive carbon black-filled system is lower than that of the unfilled CSM. With increasing filler concentration, extrudate swell drops significantly in the high shear rate region. The lower value of die-swell in filled CSM compared with gum rubber is attributed to the polymer-filler interactions, reduction in polymer content per unit volume of the compound, decrease in elastic nature and development of higher viscosities.[25] Fillers are able to make chemical/physical entanglements with polymer chains. This is in favor of storing more recoverable elastic energy and hence more extrudates swell. However, the lower extrudates swell value for the filled compositions may be due to the compensation between forming chain entanglements and the reduction in polymer content per unit volume of compound. It seems the reduction in polymer content overcomes

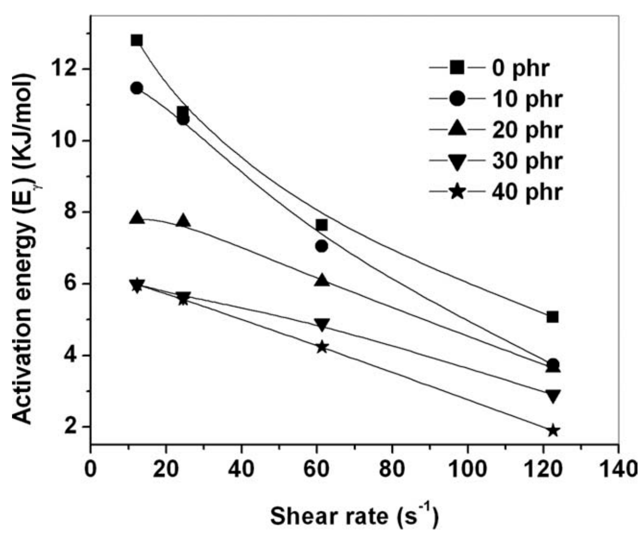

Figure 10 Variation of activation energy with shear rate for both unfilled and filled CSM composites.

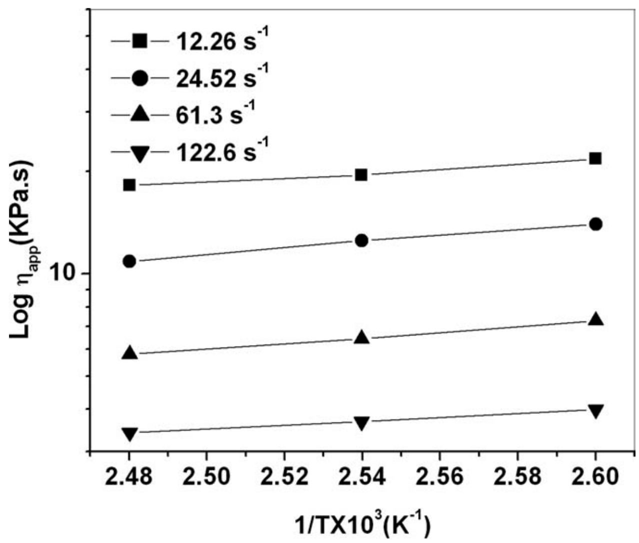

Figure 11 Apparent shear viscosity of 3 phr DOP-loaded CSM composites as a function of reciprocal temperatures ($1/T$) at various shear rates.

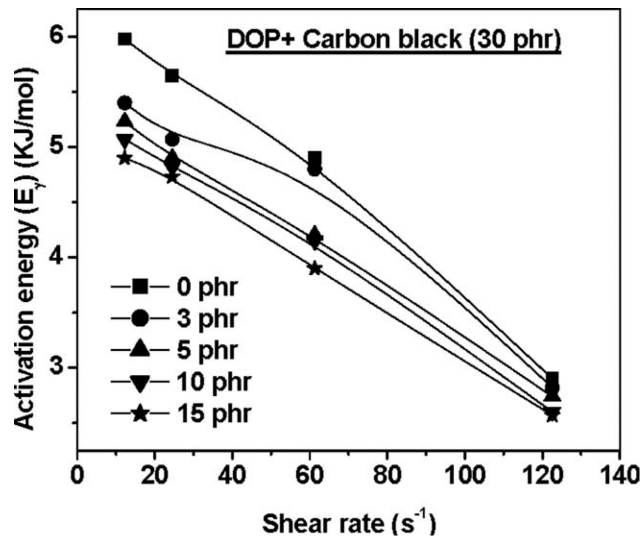

Figure 12 Variation of activation energy with shear rate for CSM composites: effect of DOP loadings.

the effect of forming chain entanglements resulting to overall reduction in melt recoverable elastic energy.

Plots of running die-swell ratio vs. apparent shear rate for the CSM composites with reference to plasticizer loadings at 130°C are given in Figure 6. Similar trends are also obtained for 110 and 120°C. There is a marked reduction in die-swell with increase in DOP dose. This is quite advantageous during processing as these conditions are normally employed in rubber extrusion. Scanning electron micrographs of the extrudates with different filler loadings and with different DOP loading are shown in Figures 7 and 8, respectively. With an increase in the carbon black loading, the extrudate roughness decreased, indicating an improvement in processing. The probable explanation could be that with an increase in the filler loading the elastic memory of the compound decreased.[2] With increase in DOP loading, the surface smoothness increases. This may be due to increase in plasticization effect, which decreases the elastic memory of the system.

Activation energy of melts flow

Activation energy of the flow process has been calculated from the slope of the plot of log (shear viscosity) vs. $1/T$ as given by eq. (7).[15] Figure 9 shows the plot between log (shear viscosity) vs. $1/T$ at various shear rates for 30 phr conductive carbon black-loaded CSM composites. Similar trends are also obtained for other filler loadings. The activation energy and standard deviation values at different shear rates were calculated for all compounds and given in Table IV. Figure 10 shows the variation of activation energy with shear rates. Activation energy gradually decreases with increasing shear rate. This decrease in activation energy with increasing shear rate may be due to: (i) orientation of the molecular segments in the direction of applied stress and (ii) increased wall slip.[26] The reduction in the activation energy of flow with increasing filler loading is observed as shown in Table IV. The incorporation and dispersion of fillers in the rubber matrix lead to (i) reduction in the molecular weight of rubber and broadening on the molecular weight distribution, (ii)

TABLE V
Calculated Values of Activation Energy (KJ/mol) and Standard Deviation of CSM Composites with Different DOP Loadings at Different Shear Rates

	Shear rate (s^{-1})							
	12.26		24.52		61.3		122.6	
Mix designation	Eγ	SD	Eγ	SD	Eγ	SD	Eγ	SD
HB_3	5.98	6.58×10^{-3}	5.65	5.08×10^{-3}	4.9	2.93×10^{-3}	2.9	1.48×10^{-3}
HB_{31}	5.4	1.45×10^{-3}	5.07	1.67×10^{-3}	4.8	1.33×10^{-3}	2.82	1.91×10^{-3}
HB_{32}	5.23	1.23×10^{-3}	4.9	4.22×10^{-3}	4.2	3.21×10^{-3}	2.74	2.45×10^{-3}
HB_{33}	5.07	1.67×10^{-3}	4.82	1.54×10^{-3}	4.15	1.62×10^{-3}	2.6	1.39×10^{-3}
HB_{34}	4.9	1.56×10^{-3}	4.73	1.47×10^{-3}	3.9	1.52×10^{-3}	2.57	2.45×10^{-3}

uncoiling and straining the molecular chains, and (iii) increase in the intermolecular distance between the polymer chains thereby decreasing the intermolecular force of attraction.[27] As the activation energy of flow is the minimum energy requirement for the molecules for initiation of flow and which is equivalent to energy necessary to overcome the intermolecular force of attraction. Thus, the activation energy decreases with increase in filler loading. Similar findings have also been reported in literature.[28]

Figure 11 shows the plot between log (shear viscosity) vs. $1/T$ at various shear rates for 3 phr DOP-loaded CSM composites. Similar trends are also obtained for other DOP loadings. Figure 12 shows the variation of activation energy of melt flow with shear rate for plasticized CSM compounds. Activation energy decreases gradually with shear rate for all samples. With the addition of DOP, the activation energy showed a marked decrease as compared with the compound containing no DOP at low shear rate. The activation energy and SD values at different shear rates have been calculated for all DOP loadings and are given in Table V.

CONCLUSIONS

In this investigation, the rheological properties of unfilled and filled CSM have been measured. All samples studied showed pseudoplastic or shear-thinning behavior. The viscosity of CSM composites is found to increase with increase in filler loadings and decrease with DOP loadings. Extrudate swell increases nonlinearly with increasing shear rate. With increase in filler loading die-swell ratio decreased. This is attributed to the limitation of the elastic recovery of the confined polymer chains by high rigid carbon black particles after capillary extrusion. The lower die-swell ratio of DOP-filled CSM composites are due to lower melt elasticity. The dependence of shear viscosity on test temperature has also been studied, and the relationship obeys Arrhenius-Frenkel-Eyring expression. The activation energy decreases with increase in both filler loading and DOP content. The activation energy decreases gradually with the increase in shear rate for all samples. The decrease in activation energy with increase in shear rate may be due to an increase in wall slip. The extrudate roughness decreases with an increase in the filler loadings, which may be due to decrease in elastic memory of the compound. The smoothness of the surface of the extrudates is also increased with increase in DOP loadings.

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