Determination of Twin-Screw Extruder Operational Conditions for the Preparation of Thermoplastic Vulcanizates on the Basis of Batch-Mixer Results

F. Goharpey, R. Foudazi, H. Nazockdast, A. A. Katbab

Polymer Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran 15875-4413, Iran

Received 13 March 2007; accepted 24 July 2007
DOI 10.1002/app.27401
Published online 7 December 2007 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: In this study, we attempted to prepare a thermoplastic vulcanizate in a twin-screw extruder by determining the screw configuration on the basis of batch-mixer results. In this regard, two sets of information were used: (1) the time length, power consumption, and filling factor of different stages of the reactive blending process in the internal mixer and (2) the mean residence time and power consumption of the twin-screw extruder. Morphological features of the samples taken from the melt-mixing and dynamic vulcanization zones of the extruder with the selected screw configuration were found to be comparable with corresponding samples taken from an internal mixer reported in our previous study. The rheological and mechanical properties could provide valuable information to support the reliability of this study. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 107: 3840–3847, 2008

Key words: compounding; modeling; morphology; reactive extrusion; rheology

INTRODUCTION

In recent years, increasing activities have been directed toward the use of twin-screw extruders in the fast-growing field of compounding and reactive processing for the production of high-performance polymeric materials.[1–3] In this regard, the determination of the screw configuration for compounding and reactive blending in twin-screw extruders has always been an interesting subject for scientists and technologists. Dynamically vulcanized thermoplastic elastomers are among important compounds that are prepared by the melt reactive mixing of a thermoplastic with an elastomer in the presence of a small quantity of a vulcanizing system, which leads to the *in situ* crosslinking of the rubber phase.[4–7] The technical importance of these materials is mainly due to their specific type of microstructure, in which the rubber phase is dispersed as tiny cured particles throughout the continuous thermoplastic matrix.[8–11] Most of research works concerned with the preparation of dynamically vulcanized thermoplastic vulcanizates (TPVs) have focused on internal mixers,[4–11] and scientific reports dealing with the preparation of TPVs in continuous mixers such as reactive extruders are very rare.[12] In our previous studies,[13,14] we examined the mechanism of morphology development parameters, in particular, affecting the formation of rubber particle agglomerates in TPVs based on ethylene–propylene–diene monomer (EPDM)/polypropylene (PP) (60/40 w/w) produced in internal mixer. The relationship between the melt linear viscoelasticity and morphology of these samples was also investigated.[15] The dynamic vulcanization process was found to be associated with a pronounced mixing torque, which was attributed to the formation of an agglomerate structure by the rubber particles through joint shell mechanism induced by interfacial enhancement.[13] The reduction of the mixing torque after the peak maxima was passed at the dynamic crosslinking stage was concluded to be due to the shear-induced breaking down of the agglomerates, which led to a well-defined, matrix-disperse-type morphology.

However, in some studies,[16,17] the screw configuration has been defined automatically with software coupled to optimization routines; the determination of the screw configuration on the basis of batch-mixer results was not yet considered. The main objective of this study was to use the information obtained by an internal mixer to select an appropriate screw configuration and adjustment of the reactive blending process conditions for the production of TPVs.

Correspondence to: F. Goharpey (goharpey@aut.ac.ir).

Journal of Applied Polymer Science, Vol. 107, 3840–3847 (2008)

THEORY

An appropriate screw configuration can be determined on the basis of identical degrees of mixing in

both devices. On the basis of the energy conservation law, two systems have equal outputs, if their efficient energy consumptions are equal:

$$\text{Input} \xrightarrow{\text{Process}_i} \text{Output and} \{\text{Output} = \text{cte}\} \quad \Rightarrow \quad \{\text{Energy}_i * \text{Efficiency}_i = \text{constant}\} \quad (1)$$

Therefore, to determine the screw configuration and operational conditions in a corotating twin-screw extruder, the following two sets of information were used:

1. The time length, power consumption, rotor speed, and filling factor associated with different stages of the reactive blending process, including PP melting, PP/EPDM melt mixing, and the dynamic vulcanization process, in an internal mixer together with the rheological properties of the materials at each of the stages.
2. The residence time, power consumption, apparent shear rate, and volumetric feeding rates of the twin-screw extruder determined on the basis of the total screw volume, basic process power consumption, apparent shear rate estimation, and filling factor.

The screw speed was evaluated by equalization of the apparent shear rate of the internal mixer ($\dot{\gamma}_{\text{int}}$) with that of the twin-screw extruder ($\dot{\gamma}_{\text{Twin}}$), which are expressed, respectively, by the following equations:

$$\dot{\gamma}_{\text{Int}} = \frac{2\pi N_i}{\text{Ln}(R_o/R_i)} \quad (2)$$

$$\dot{\gamma}_{\text{Twin}} \cong \frac{\pi N_s D_e}{h_m} \quad (3)$$

where N_i, R_o, and R_i are the rotor speed, chamber radius, and rotor radius of the internal mixer, respectively; N_s is screw speed, D_e is the equivalent screw diameter of twin-screw extruder, and h_m is the average channel depth in the conventional channel transverse direction, which is defined by the following relation:

$$h_m = \frac{1}{A}\int h \cdot dA \quad (4)$$

where h is the channel depth and A is the channel cross-section area.

One can determine the mean residence time of each screw section i as follows:

$$\bar{t}_i = \frac{V_{\text{occ},i}}{Q_i} \quad (5)$$

where $\bar{t}_i$ is the mean residence time, $V_{\text{occ},i}$ is the occupied polymer melt volume, and Q_i is the volumetric flow rate of that section.

If the screw consisting of partially filled and fully filled sections is considered, the filled volume of the partially filled section (V_f) can be determined as follows:

$$V_f = V\frac{Q_i}{Q_c} \quad (6)$$

where V is the total volume of the partially filled screw section, which can be calculated according to the method introduced by Booy,[18] and Q_c is the maximum volumetric flow rate in the fully filled condition, which is defined as follows:

$$Q_c = \frac{\pi^2}{2}hD^2N_s\tan\varphi_s \quad (7)$$

where D is the screw diameter and ϕ_s is the screw helix angle.

From the previous equations, the mean residence time of each extruder section consisting of partially filled and fully filled subsections is defined as follows:

$$\bar{t}_i = \bar{t}_{1,i} + \bar{t}_{2,i} \quad (8)$$

where $\bar{t}_{1,i}$ and $\bar{t}_{2,i}$ are the mean residence times of the partially filled and fully filled subsections, respectively. Thus, from eqs. (5) and (6), the mean residence times for the two subsections are

$$\bar{t}_{1,i} = \frac{V_{f,i}}{Q_i} = \frac{V_{PF,i}}{Q_c} \quad (9)$$

$$\bar{t}_{2,i} = \frac{V_{FF,i}}{Q_i} \quad (10)$$

where $V_{PF,i}$ and $V_{FF,i}$ are the extruder chamber volumes of the partially filled and fully filled subsections, respectively; therefore, the total chamber volume of each extruder section is $V_i = V_{PF,i} + V_{FF,i}$. The volumes of these subsections can be calculated according to Booy et al.[18] as follows:

$$V_{PF,i} = 2k_oR_s^3(L_i - L_{f,i})/D \quad (11)$$

$$V_{FF,i} = 2k_oR_s^3(L_{f,i}/D) \quad (12)$$

where R_s is the screw radius, D is the screw diameter, $L_i - L_{f,i}$ is the fully filled subsection length, $L_{f,i}$ is the partially filled subsection length, and k_o can be calculated by the following equations:

$$k_o = k_{BC} - 2k_D \quad (13)$$

$$k_D = n[\psi\rho_c^2 - \rho_c\sin\psi + \frac{1}{2}\alpha(\rho_c - 1)^2] \quad (14)$$

$$k_{BC} = 2(\pi - \psi) + \rho_c\sin\psi \quad (15)$$

$$n(2\alpha + 4\psi) = 2\pi \quad (16)$$

where ρ_c, α, and n are the centerline distance ratio, tip angle, and number of tips, respectively. Thus, the

mean residence time of each section can be determined as follows:

$$\bar{t}_i = k_o R_s^2 \left(\frac{L_i - L_{f,i}}{Q_c} + \frac{L_{f,i}}{Q_i} \right) \quad (17)$$

In open-discharge conditions, the negative pitch and/or kneading elements of the screw are operated in the fully filled condition, and therefore, due to the equality of the kneading disk cross section to that of the conventional screw, the chamber volume of subsections, including the negative pitch and/or kneading zone, can also be determined from the previous equations.

The total power transmitted from the main motor to the screws of the twin-screw extruders in open-discharge conditions (Z_t) can be determined as follows:[19]

$$Z_t = \mu \dot{\gamma}^2 V_{FF} + \left(\frac{\pi^2 D^2 e C_e}{\delta} + \frac{8\pi^2 C_l^3 e}{\varepsilon} + \frac{4\pi C_l^2}{\sigma} \right) \mu N_s^2 N_f \quad (18)$$

where e, δ, ε, σ, μ, C_l and N_f are the flight tip width, clearance between the tips of the screws and the barrel, the clearance between the screws tips and the channel bottoms, the distance between the flanks, the polymer melt viscosity, the center-line distance, and the number of filled flights; and C_e is

$$C_e = 2(\pi D - \sqrt{2\pi D}) \quad (19)$$

N_f can be calculated by the following equation:

$$N_f = \frac{L_f}{p} = \frac{L_f}{\pi D \tan \varphi_s} \quad (20)$$

where p is the screw pitch. Thus, the power consumption for each section can be determined from eq. (21)

$$Z_{t,i} = \left(\frac{\pi^2 k_0 R_s^2 D_e^2}{h_m^2} + \frac{\pi D e C_e}{\delta \tan \varphi_s} + \frac{8\pi C_l^3 e}{\varepsilon D \tan \varphi_s} + \frac{4 C_l^2}{\sigma D \tan \varphi_s} \right) \times \mu_i N_s^2 L_{f,i} \quad (21)$$

or eq. (22) as follows:

$$Z_{t,i} = f_i(\text{Geometry}) \times \mu_i N_s^2 L_{f,i} \quad (22)$$

Because of the equality of the flow section of the full field channel with that of the kneaders, the previous methodology [eq. (22)] can also be applied to calculate the power consumption of the screws with kneaders.

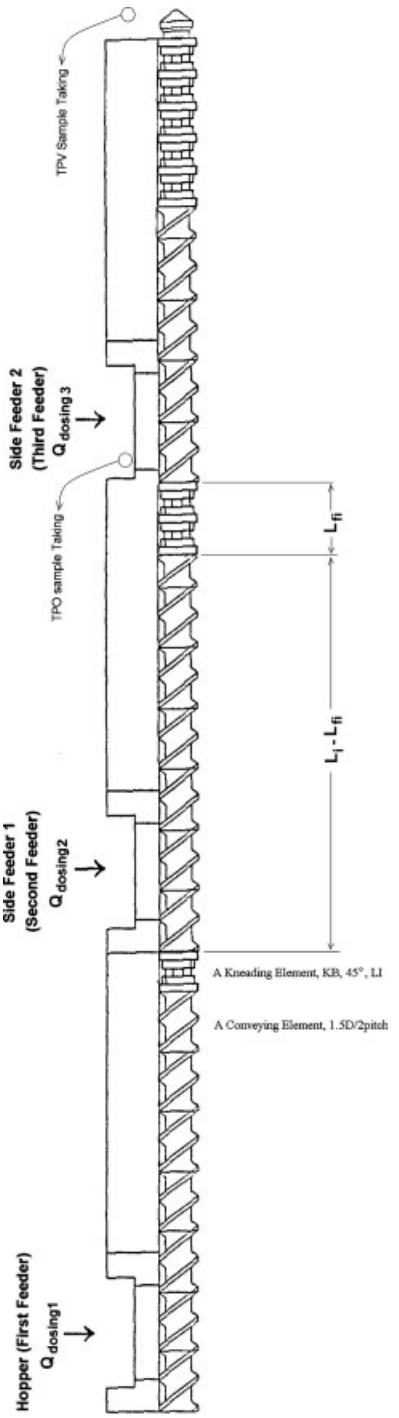

Figure 1 Schematic view of the screw configuration of a twin-screw extruder (L_i = ith section length, L_{fi} = kneading-zone length, $L_i - L_{fi}$ = conveying-zone length).

With the internal mixer with three different feeding zones (Fig. 1) considered, the screw was divided into three sections. Similar to most conventional extruders, we could divide the screw into three equal lengths ($L_1 = L_2 = L_3$).

The filling factor of different sections of twin-screw extruder (f_i) was assumed to be equal with

the corresponding stages of an internal mixer; therefore

$$\frac{Q_i}{Q_c} = f_i \tag{23}$$

With the previous equations considered, the dosing rates of the feeders could be determined as follows:

$$Q_i = \sum_{j=1}^{i} Q_{\text{dosing},j} \tag{24}$$

where $Q_{\text{dosing},j}$ is the dosing rate of i-th feeder.

On the basis of the power consumption estimation, it was concluded[20] that extensional flows are more efficient than shear flows in mixing. To quantify the elongational and shear flow components and, thus, to define the character of the flow field, Yang and Manas-Zloczower[21] introduced a parameter λ, defined as:

$$\lambda = \frac{|\underline{\underline{\Delta}}|}{|\underline{\underline{\Delta}}| + |\underline{\underline{\omega}}|} \tag{25}$$

where $|\underline{\underline{\Delta}}|$ and $|\underline{\underline{\omega}}|$ are the magnitude of the rate of deformation tensor and the vorticity tensor, respectively. The values of λ vary between 0 for pure rotation and 1 for pure elongation, with 0.5 being the familiar case of simple shear flow. On the basis of the energy conservation law, the two systems have equal outputs if their efficient energy consumptions are equal. Therefore, λ can be considered as the weighting function of flow field efficiency, that is

$$\text{Input} \xrightarrow{\text{Process}_i} \text{Output and} \{\text{Output} = \text{cte}\} \Rightarrow \{\text{Residence time}_i * \text{Power}_i * \lambda_i = \text{cte}\} \tag{26}$$

By equalizing the efficient energy in an internal mixer and a twin-screw extruder, one can determine the filled or mixing length ($L_{f\,i}$) of each screw section as follows:

$$\left(\lambda_i \times \int T_i \times N_i \times dt_i\right)\Big|_{\text{Int}} = \left(\lambda_i \times Z_i(L_f) \times t_i(L_f)\right)\Big|_{\text{TSE}} \tag{27}$$

where T_i is the torque variation versus time in the i-th stage of internal mixer.

It has been suggested that the values of λ for internal mixers[21] and twin-screw extruders[22] are almost equal. Therefore, by equalization of the total energy, which can be defined as the multiplication of mean residence time and power, of the corresponding stages and sections in the internal mixer and twin-screw extruder, L_{fi} of each screw section can be determined. In open-discharge conditions, the mixing zones of the screw are operated in the fully filled condition; therefore, one can consider L_{fi} the mixing-zone length.

From eqs. (24) and (27), the length of the screw conveying elements ($L_i - L_{fi}$), L_{fi}, and feeding rates of the components in a corotating twin-screw extruder can be determined.

EXPERIMENTAL

Materials

The basic characteristics of the polymers used in this study are listed in Table I. Injection-grade PP from Himont Co. (Italy) and EPDM based on ethylidene norbonenet (ENB) as a diene monomer (Keltan), supplied by DSM Elastomers Europe (Netherlands), were used as commercially available.

Blend preparation

The melt reactive blending processes for the preparation of TPV samples composed of 60/40 w/w/ EPDM/PP were performed both in an internal mixer and in a corotating twin-screw extruder. The first set of samples was prepared in a small-scale laboratory Haake (USA) internal mixer (Rhecord 90) at a rotor speed of 60 rpm and temperature of 180°C and with a filling factor 75%. We performed the blending process by first feeding the PP; after 2 min, EPDM was added, and mixing was continued until the mixing torque reached the steady state. Then, the crosslinking ingredients were fed into the melt mixture. The variation of mixing torque versus time was recorded for the blending process. To follow the morphological development during the melt blending, samples of the melt-blending and dynamic vulcanization stages were removed without interruption of the mixing process. The samples were cooled at room temperature before they were examined by scanning electron microscopy (SEM). The second set of the samples was prepared in a modular corotating twin-screw extruder (Brabender DSE25, Duisburg, Germany) with a screw diameter of 2.5 cm, a length/diameter ratio of 32, and a distance between the two axes of 20.87 mm. The screw configuration was determined on the basis of the theoretical studies presented in this article. In this process, as shown in Figure 1, PP was fed through the hopper (first) feeder of the extruder, and EPDM was fed through

TABLE I
Characteristics of the Materials

Material	Characteristic	Value
PP	Melt flow index	6.0 g/10 min
	Density	0.9 g/cm^3
	Melting temperature	165°C
EPDM	Mooney viscosity [ML(1 + 4), 125°C]	77
	Ethylene content	52%
	Termonomer content	4.5%
	Density	0.89 g/cm^3
	Curing rate	Fast
Maleated PP	Melt flow index (2.160/230)	90 g/10 min
	Maleic anhydride grafting	1%

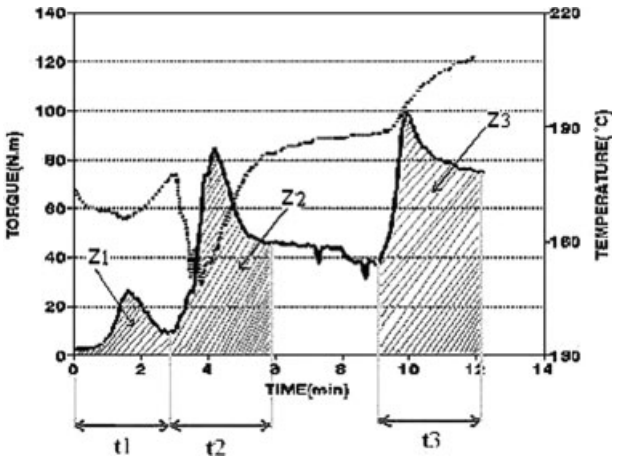

Figure 2 Variation of the (—) torque and (· · ·) temperature versus time at different mixing stages for the preparation of the EPDM/PP (60/40 w/w) dynamically cured ThermoPlastic Elastomer (TPE).

the side (second) feeder, which was positioned at some distance beyond the melting and the first mixing elements of the twin-screw extruder, which allowed the melt mixing to be completed. The curing system was added to the molten mixture through the next side (third) feeder, which allowed the curing ingredients to be well mixed with the melt mixture in the mixing elements where the dynamic vulcanization process began. All of the blends were dynamically cured with a vulcanizing system based on 100 phr EPDM, 5 phr ZnO, 1.5 phr stearic acid, 1.5 phr tetra methyl thiuram disulfide (TMTD), 0.9 phr dibenzothiazole disulfide (MBTS), and 1.4 phr sulfur. To follow the morphological development, the uncured sample was taken out of the melt-blending section of the extruder, and the cured sample was removed from the extruded TPV (Fig. 1).

Morphology studies

To study the morphology of the blend samples at various stage of mixing, cryogenically fractured surfaces of the samples were stained by OsO_4 vapor for 4 h and etched by hot xylene for 30 s. The treated samples were then sputter-coated with gold and viewed with a scanning electron microscope (Philips model XL30, Netherlands).

TABLE II
Fill Factor of Different Stages of Internal Mixer and Correspondence Dosing Rates in Twin Screw Extruder

Stage (Internal mixer) or Section (Twin Screw extruder), *i*	First (PP feeding)	Second (EPDM feeding)	Third (Curing System feeding)
Fill Factor, f_i (%) (Internal Mixer)	28.275%	70.65%	75%
Dosing Rates, Q_i (cm^3/sec) (Twin Screw Extruder)	1.179	1.767	0.181

Rheological studies

The melt viscoelastic properties of the samples were studied with a rheometric mechanical spectrometer (Paar Physica USD 200, Austria) equipped with geometry with diameter of 25 mm. To determine the strain amplitude range over which the linear viscoelasticity prevailed, amplitude sweep experiments at a frequency of 5 rad/s in an overall amplitude range of 0.1–100 were conducted. From these experiments, the 1% strain amplitude was selected for frequency sweep tests. All measurements were performed at a temperature of 220°C.

Measurement of the mechanical properties

The tensile properties of the prepared samples were studied according to ASTM D 412 at room temperature with a crosshead speed of 50 mm/min with a tensile tester machine (model Monsanto 5KN, USA). To prepare the test specimens, a room-temperature cooled blend sample was ground and put into the cavity of a hot mold. After 2 min of preheating, the sample was compression-molded at 150 bar. Sheets 2 mm thick were cut into dumbbell-shaped specimens with dimensions according to ASTM D 412.

MODEL VERIFICATION AND DISCUSSION

Figure 2 illustrates a typical curve of mixing torque versus time for the preparation of the dynamically crosslinked EPDM/PP (60/40, w/w) blend system in an internal mixer. The first and second torque peaks corresponded to the feeding of PP and EPDM into the mixer, respectively. The third peak was associated with the *in situ* crosslinking of the dispersed rubber droplets.[13] The mixing torque dramatically increased as the vulcanization of the rubber droplets started and, after a maximum was passed,

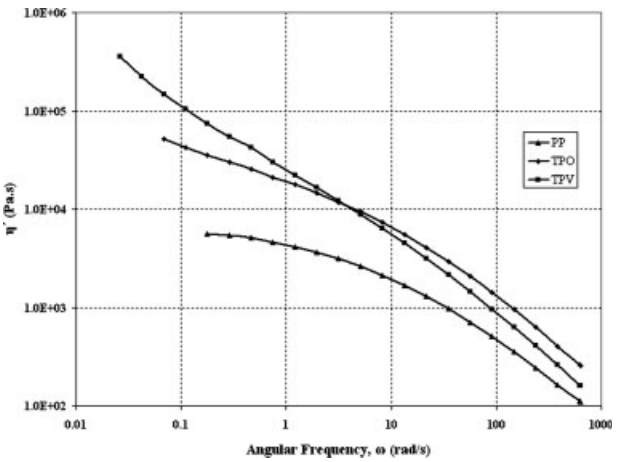

Figure 3 Diagram of η′ as a function of ω for the neat PP, TPO, and TPV.

TABLE III
Screw Configuration

Subsection length	$L_1 - L_{f,1}$	$L_{f,1}$	$L_2 - L_{f,2}$	$L_{f,2}$	$L_3 - L_{f,3}$	$L_{f,3}$
Configuration	Conveying element[a]	Mixing element[b]	Conveying element[a]	Mixing element[b]	Conveying element[a]	Mixing element[b]
Value (cm)	248	18	234	32	193	75

[a] Two-tip conveying element with a 25-mm screw diameter and a 20.87-mm centerline distance.
[b] Two-tip kneading element with the same characteristics as the conveying element.

declined to a stationary level. In our previous work, we demonstrated that the pronounced increase in the mixing torque observed during the dynamic vulcanization stage was associated with the formation of the cured rubber agglomerates in the PP matrix by a joint shell mechanism.[14]

From the previously discussed theory, an appropriate screw configuration and operational conditions in the corotating twin-screw extruder for the preparation of the TPV sample were determined.

The screw speed was evaluated by equalization of the apparent shear rate of the internal mixer with that of twin-screw extruder [eqs. (1) and (2); N_s = 212 rpm).

By calculating the filling factor of different sections of the twin-screw extruder, which was assumed to be equal with corresponding stages of the internal mixer, we determined the dosing rates of each feeder of the twin-screw extruder using eqs. (7), (23), and (24) (Table II).

By considering eq. (27), to determine the energy consumption of the internal mixer in the different mixing stages (Fig. 2), we calculated the integral of the torque curve versus time correspond to each stage.

To determine the power consumption for each section of the screw extruder [Z_i, eq. (22)] and, therefore, determine L_{fi} of each screw section [eq. (27)], the variation of viscosity versus shear rate for PP, the uncured EPDM/PP blend (TPO), and the dynamically vulcanized EPDM/PP blend (TPV), which was prepared in the internal mixer, were measured (Fig. 3).

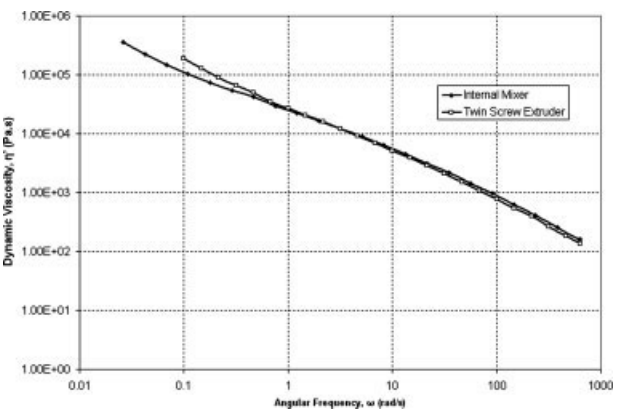

Figure 4 Diagram of η' as a function of ω of the dynamically vulcanized TPV samples taken from an internal mixer and twin-screw extruder.

The results shown in Figures 2 and 3 were used in the previously discussed equations to determine the screw configuration for the preparation of the TPV sample with the 60/40 w/w EPDM/PP composition. The quantitative values predicted for $L_i - L_{fi}$ and L_{fi} in the twin-screw extruder corresponding to Figure 1 are presented in Table III. Similar to the conventional configuration of twin-screw extruders, the kneading zones were considered in the end of each section. The selected mixing modules were two-tip-type kneading disks with the cross section equal to the screw elements.

To evaluate the validity of the model, the melt viscoelastic properties and morphology development of the TPV samples prepared in both the internal mixer and the twin-screw extruder with the determined screw configuration were studied.

Figure 4 shows the dynamic viscosity (η') versus angular frequency (ω) of the dynamically vulcanized TPV samples taken from the internal mixer and twin-screw extruder. As shown, the flow behavior of the TPV samples prepared in the twin-screw extruder were in close agreement with that prepared in the internal mixer. These results suggest similar morphological features for both of these samples.

Figure 5 shows the SEM micrographs of the uncured EPDM/PP blend samples taken from the internal mixer and twin-screw extruder during the melt-mixing process. The average rubber droplet size of these blend samples measured by the image analysis method are given in Table IV. These results clearly demonstrate the significant role of coalescence on the dispersed droplet size during sampling. Figure 6 shows the SEM micrographs of the TPV samples taken from the dynamic vulcanization stage in the internal mixer and twin-screw extruder. The average rubber domain sizes of these cured blend samples are given in Table IV. The higher domain

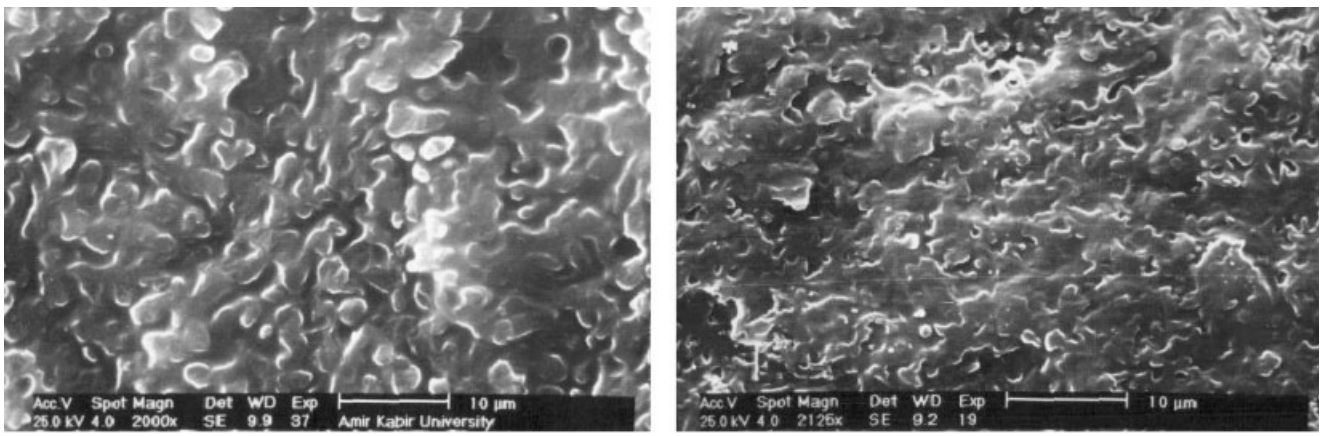

Figure 5 SEM micrograph of a frozen, uncured EPDM/PP (60/40 w/w) blend sample during the melt-mixing stage taken from (left) an internal mixer and (right) a twin-screw extruder.

sizes in the cured samples were due to the aggregation of rubber particles through the joint shell mechanism.[14] Differences between the droplet size and extent of agglomeration in these two samples taken from the internal mixer and twin-screw extruder could be explained in terms of the differences between the geometry and flow field imposed in the two mixers. Although the extent of shear rate and the efficient energy consumption in the twin-screw extruder and internal mixer were considered to be the same, the diversity of states of stresses in the twin-screw extruder was much greater than that in the internal mixer. This could have led to a smaller rubber particle size and a lower extent of agglomerates observed for the TPV samples taken from the twin-screw extruder, as shown in Figures 5 and 6. Figure 7 shows the elastic modulus of the TPV sample produced by the internal mixer compared to the sample prepared in the twin-screw extruder. This results provide good evidence to support the previously discussed theory. The slightly lower elasticity of the twin-screw extruder TPV sample exhibited at low shear rates was attributed to the lower extent of agglomerate formation enhanced by the decreased rubber domain sizes regarding the difference between the flow fields in the internal mixer and twin-screw extruder.

TABLE IV
Domain Sizes

D (µm)	Internal mixer	Twin-screw extruder
Droplet size (uncured samples)	1.8	1.6
Aggregate size (cured samples)	2.8	2.4

The results of stress–strain testing performed on the TPV samples taken from the internal mixer and the twin-screw extruder are presented in Table V. These results show that despite the lower extent of agglomerates observed for the TPV samples taken from the twin-screw extruder, there was a uniform agglomerate distribution of cured rubber particles in this sample.

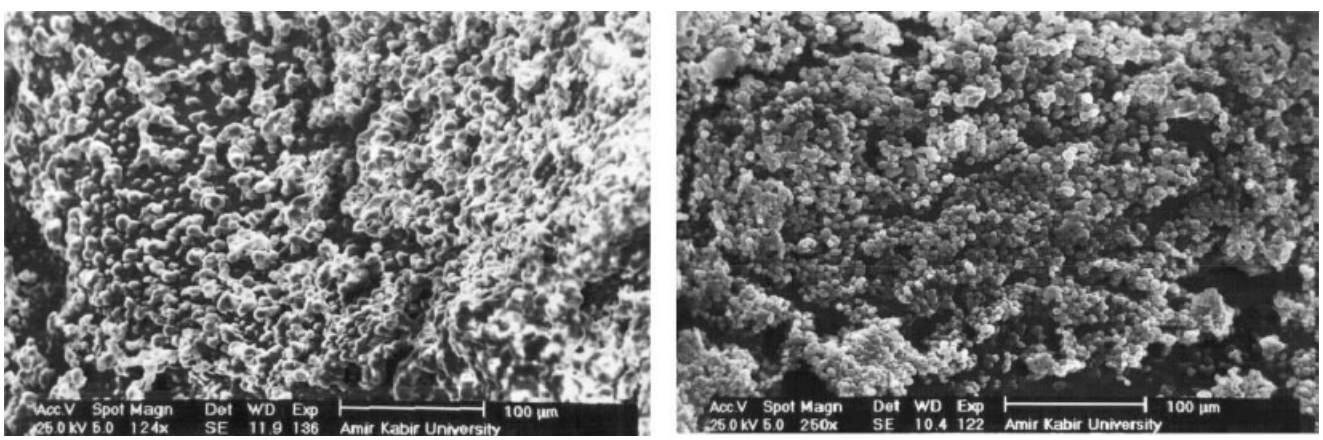

Figure 6 SEM micrographs of dynamically crosslinked EPDM/PP blend samples from the dynamic vulcanization stage in (left) an internal mixer and (right) a twin-screw extruder.

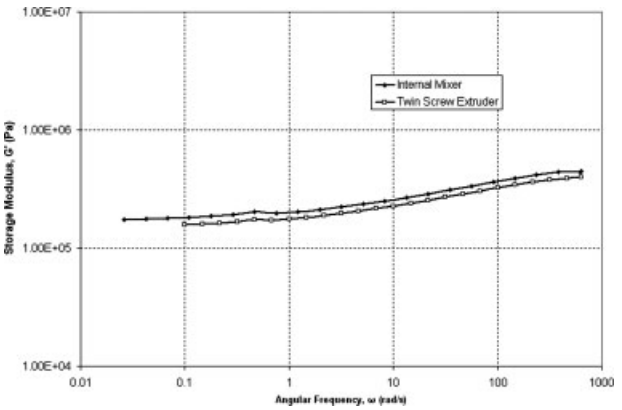

Figure 7 Diagram of the storage modulus (G') as a function of ω of dynamically vulcanized TPV samples taken from an internal mixer and a twin-screw extruder.

Despite some slight differences between the microstructure of the sample prepared in the twin-screw extruder on the basis of batch-mixer results with that prepared in internal mixer, this model can be used as a new mixer scaling model and can also be used to determine the screw configuration in simple blending and reactive extrusion processes. The model can be developed by modification through simplification assumption modification.

CONCLUSIONS

We demonstrated that it is possible to determine the length of screw transport elements with positive pitch and mixing-zone length as well as blend component feeding rates in a corotating twin-screw extruder for the preparation of dynamically vulcanized thermoplastic elastomers (TPVs) based on EPDM/PP (60/40 w/w) on the basis of the experimental data obtained for a similar blend system in an internal mixer.

A comparison of the microstructure and viscoelastic properties of the TPV samples (EPDM/PP, 60/40 w/w) prepared in an internal mixer and twin-screw extruder taken from the melt mixture in the dynamic vulcanization stage suggested slight differences between the particle size and extent of agglomeration in these two samples. The properties of the TPV samples produced in the twin-screw extruder suggested a slightly lower extent of cured rubber agglomerates but a more uniform agglomerate size distribution for this sample; this observation was attributed to a higher state of stresses in the twin-screw extruder in comparison to the internal mixer.

This approach can also be used for other applications, such as mixing and reactive extrusion processes, and can be developed by modification through simplification assumption modification.

TABLE V
Mechanical Properties

	Tensile strength (MPa)	100% modulus (MPa)	Elongation at break (%)
Internal mixer	19	6.9	485
Twin-screw extruder	20	6.7	497

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