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Compression behavior and tensile strength of heat-treated polyethylene glycols

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Abstract

The compression behavior and tensile strength of five heat-treated polyethylene glycol (PEG) powders of different average molecular weights were determined. Compacts were prepared at various compression pressures using three different size fractions. The compression behavior of the compacts was analyzed according to the Kawakita, Cooper-Eaton and Heckel methods, respectively, and their compression parameters were calculated. Compared to the other polymers, PEG 4000 underwent greater densification during compression. The yield pressure from the slope of the Cooper-Eaton plot was lowest for PEG 4000. The yield pressure determined via the Heckel method was found to be proportional to the molecular weight of the PEG. These polymers obey a Heckel relationship at lower pressures (not exceeding 80 MN/m^2) and exhibit a behavior similar to those of fatty acid powders. The specific surface area of the compacts decreased with increasing compression pressure. The change in specific surface area of compacts compressed at pressures greater than 80 MN/m^2 was only very slight. This indicates that the surface of the compacts melts at such pressures. At pressures above 26.53 MN/m^2, PEG 10000 compacts had superior tensile strength compared to the other polymers.

Keywords: Solid dispersion; Polyethylene glycol; DSC; Kawakita plot; Cooper-Eaton plot; Heckel plot; Tensile strength

1. Introduction

Solid dispersions require formulation into dosage forms, namely, either tablets or capsules. For the former, it has been reported that either simple direct compression or double compression techniques are acceptable for maintaining their fast release characteristics (Ford, 1986). However, the incorporation of large concentrations of carriers into tablets is not without problems since some, especially PEG, may cause capping of tablets following compression (Ravis and Chen, 1981). In order to produce acceptable tablets of solid dispersions using PEG as carriers, it is necessary to have an understanding of the solid structure and of the compaction properties of the carriers.

The polyethylene glycols are a series of water-soluble synthetic polymers, the repeating unit being oxyethylene (-OCH$_2$CH$_2$-) with either end of the chain comprising an hydroxyl group (Craig,

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1990). Polyethylene glycol solid dispersions may be readily manufactured using the fusion method due to the low melting point. The changes in the solid structure of PEG depend on the thermal history of the samples (Craig and Newton, 1991). It has been demonstrated that the temperature of fusion and cooling rate may have a profound effect on the solid structure of PEG 6000 itself and drug dissolution in tolbutamide-PEG 6000 solid dispersion systems (McGinity et al., 1984).

Significant differences in the mechanical strength of PEG depend on heat treatment. The mechanical properties of pure PEG molded tablets have been shown to be highly sensitive to thermal history (Fassihi et al., 1977). Knowledge of the compression behavior of heat-treated PEG powders may be valuable in selecting a potential polyethylene glycol for direct compression of solid dispersions. It is also important to characterise the structure of the polyethylene glycols in order to standardise product performance.

The purpose of this investigation was to describe the compaction and compression behavior of a range of PEG powders of different molecular weight which were subjected to prior heat treatment.

2. Materials and methods

Five polyethylene glycols of nominal molecular weights 4000 (Riedel-deHaen, lot no. 81810), 6000 (Lux, lot no. 041826), 8000 (Lux, lot no. NA084926), 10 000 (Riedel-deHaen, lot no. 11130) and 20 000 (Merck, lot no. 1293021) were selected without further purification in this study. The same batch of each molecular weight sample was used throughout the study.

2.1. Preparation of heat-treated PEG samples

Heat-treated PEG samples were prepared as follows: 50 g of each PEG sample was heated directly on a hot plate (Corning, USA) from room temperature to 80°C and held at the latter temperature for 30 min. The melted samples were then rapidly cooled by immersing the containers in a freezing mixture consisting of ice and sodium chloride. The rapid-cooled samples were then stored over phosphorus pentoxide in a desiccator for 24 h. They were then lightly ground and sieved on a sieve shaker (Retsh, Germany). Sieve fractions of 425–250, 250–150 and 150–90 μm were collected, respectively, and stored in a desiccator at room temperature for at least 48 h prior to further investigation.

2.2. Differential scanning calorimetry studies

Studies were performed using a Perkin-Elmer differential scanning calorimeter (DSC 7, USA). Samples of 6.0–6.5 mg were weighed into aluminium pans and sealed non-hermetically. Samples were run from 30 to 110°C at a scanning rate of 10°C/min. All studies were repeated three times.

2.3. X-ray powder diffraction studies

Diffraction patterns of the samples were obtained by scanning at 1/min through the 2θ angle on a diffractometer (Siemens D 500, Germany) using Cu-Kα radiation.

2.4. Powder characterization of heat-treated polyethylene glycols

The bulk density of all powders was determined by pouring 30 g of the powder into a 100 ml graduated cylinders and measuring the volume of the powder. The true density of all powders was evaluated using a helium gas pycnometer (Quantachrome MVP-1, USA). The tap density of all powders was determined using a tap density tester (Van Kel, USA). To ascertain the volume occupied by the powder in the die, excess powder was poured into the die and then tapped and scraped level with the top of the die. Based on this volume, the die density was calculated subsequently. The specific surface area of all powders was determined using a surface area tester (Micromeritics FlowSorb 2300, USA) with a 30% N_2/He mixture. The water content of all powders was determined on a Karl Fisher apparatus (Metrohm, Germany).

2.5. Compression of compacts

The rapid-cooled PEG samples were compressed manually on a hydraulic press (Carver, USA). A weighed quantity (0.4 g) of powder was quantitatively transferred into a 10 mm diameter die. The pressure was increased to the preset maximum axial pressure and maintained there for 5 s, after which the pressure was quickly released. The compacts were removed and stored in an air-tight jar for 24 h prior to further study. The thickness, weight and diametral compression crushing strength (CT 40, Engineering System, UK) were determined subsequently. The tensile strength was calculated using the equation derived by Fell and Newton (1970).

3. Results and discussion

3.1. Thermal analysis studies

The melting behaviors of the five heat-treated PEG samples and untreated PEG samples are given in Table 1. Their melting points increased with increasing molecular weight. In all cases, the value of the heat of fusion (ΔH) showed little differences between the samples when calculated on a weight basis. The melting endotherms of all of the heat-treated PEG samples exhibited only one peak except for PEG 6000. The melting points of the heat-treated PEG samples were higher than those given in Table 1 for the untreated PEG samples. Difference in the particle size did not have a significant effect on their melting endotherms or melting shapes.

3.2. X-ray diffraction studies

The X-ray diffraction patterns of the five heat-treated PEG samples and untreated PEG samples are illustrated in Fig. 1. All of the untreated PEG samples exhibited some crystallinity as indicated by the two peaks of high intensity ($2\theta = 19.2$, $2\theta = 23.4$) and some other peaks of lower intensity. The heat-treated PEG samples also demonstrated the presence of similar peak characteristics but minor changes in the intensity of some peaks were seen with them. These results indicated that the solid crystallinity of the heat-treated PEG samples may have been changed during heat treatment.

3.3. Powder properties

The powder properties of three size fractions of the heat-treated PEG samples are listed in Table 2. Differences in the particle size of the

Table 1
Melting point (T_m, °C) and heat of fusion (ΔH_f, J/g) values of the polyethylene glycols using DSC (mean ± SD, $n = 3$)

Molecular weight	Size fractions	Heat-treated samples		Untreated samples	
		T_m (°C)	ΔH_f (J/g)	T_m (°C)	ΔH_f (J/g)
PEG 4000	425–250 μm	59.9 ± 0.2	187.9 ± 1.9	58.7 ± 0.2	182.6 ± 2.4
	250–150 μm	59.8 ± 0.2	188.4 ± 6.9	58.9 ± 0.1	187.8 ± 5.9
	150–90 μm	59.8 ± 0.3	184.9 ± 4.5	59.6 ± 0.4	186.8 ± 6.7
PEG 6000	425–250 μm	61.7 ± 0.3	191.1 ± 1.4	59.9 ± 0.6	188.2 ± 4.8
	250–150 μm	61.9 ± 0.2	209.6 ± 9.6	59.8 ± 0.5	189.2 ± 6.8
	150–90 μm	61.1 ± 0.7	187.6 ± 6.4	59.2 ± 0.1	186.1 ± 6.9
PEG 8000	425–250 μm	61.6 ± 0.4	189.6 ± 7.6	59.6 ± 0.4	189.8 ± 4.2
	250–150 μm	61.5 ± 0.2	193.6 ± 8.9	59.3 ± 0.6	192.6 ± 4.9
	150–90 μm	61.9 ± 0.6	196.1 ± 9.8	59.1 ± 0.3	185.1 ± 3.5
PEG 10000	425–250 μm	61.9 ± 0.2	192.5 ± 5.6	60.3 ± 0.6	189.8 ± 4.1
	250–150 μm	62.1 ± 0.4	182.6 ± 6.7	60.1 ± 0.2	181.8 ± 9.8
	150–90 μm	62.5 ± 0.1	195.5 ± 7.9	60.3 ± 0.1	186.9 ± 9.5
PEG 20000	425–250 μm	64.1 ± 0.6	190.9 ± 5.5	61.9 ± 0.2	187.8 ± 8.8
	250–150 μm	64.1 ± 0.5	191.5 ± 4.2	61.8 ± 0.8	185.8 ± 8.5
	150–90 μm	64.3 ± 0.2	188.7 ± 2.9	62.1 ± 0.3	186.9 ± 7.9

five PEG samples exert a significant effect on their powder properties. All the polymers differ from each other in their true density, bulk density, tap density and die density.

PEG 4000 has a relatively higher specific surface area than the other PEG samples studied. Only very small differences in Carr's index among the samples were observed.

3.4. Compression behavior

The Kawakita equation was developed to study powder compression (Kawakita and Ludde, 1970/1971) using the degree of volume reduction (C) and is expressed as:

$$C = (V_0 - V_p)/V_0 = abP/(1 + bP) \quad (1)$$

In practice, the Kawakita equation can be rearranged to give:

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \quad (2)$$

where C is the degree of volume reduction, V_0 denotes the initial volume of the powder bed and V_p is the powder volume after compression. The constant a is equal to the porosity of the powder

Table 2
Powder properties of three size fractions of heat-treated polyethylene glycols

Property	PEG 4000	PEG 6000	PEG 8000	PEG 10000	PEG 20000
ρ_e (g/cm^3)					
425-250 μm	1.217	1.212	1.214	1.202	1.189
250-150 μm	1.218	1.213	1.216	1.205	1.194
150-90 μm	1.218	1.213	1.217	1.206	1.196
ρ_b (g/cm^3)					
425-250 μm	0.559	0.575	0.575	0.581	0.554
250-150 μm	0.475	0.562	0.563	0.547	0.536
150-90 μm	0.433	0.481	0.490	0.479	0.476
D_b (ρ_b/ρ_e)					
425-250 μm	0.459	0.474	0.474	0.483	0.466
250-150 μm	0.390	0.463	0.463	0.454	0.449
150-90 μm	0.356	0.397	0.403	0.397	0.398
ρ_t (g/cm^3)					
425-250 μm	0.625	0.651	0.652	0.643	0.621
250-150 μm	0.588	0.636	0.639	0.618	0.611
150-90 μm	0.542	0.598	0.599	0.595	0.589
ρ_d (g/cm^3)					
425-250 μm	0.637	0.653	0.653	0.659	0.632
250-150 μm	0.598	0.641	0.642	0.626	0.614
150-90 μm	0.551	0.601	0.609	0.598	0.594
SSA (m^2/g)					
425-250 μm	0.198	0.168	0.172	0.174	0.177
250-150 μm	0.414	0.207	0.212	0.239	0.222
150-90 μm	0.494	0.297	0.322	0.323	0.297
Carr's index (%)					
425-250 μm	10.56	11.67	11.81	9.64	10.79
250-150 μm	19.21	11.64	11.89	11.48	12.27
150-90 μm	20.11	19.57	18.20	19.49	19.19
Moisture content (%)					
425-250 μm	1.585	0.972	0.747	0.758	1.089
250-150 μm	1.519	0.833	0.719	0.918	1.126
150-90 μm	1.558	0.743	0.736	1.167	1.173

ρ_e, true density; ρ_b, bulk density; D_b, relative bulk density; ρ_t, tap density; ρ_d, die density; SSA, specific surface area; Carr's index = $(\rho_t - \rho_b)/\rho_t$.

bed prior to compression while the constant *b* is related to the plasticity of the powder.

Fig. 2 shows Kawakita plots for the five heat-treated PEG samples. The results also demonstrate a good linear correlation at all of the compression pressures and therefore the equation may be used to predict the consolidation mechanisms of these polymers. The compression parameters which derived from the Kawakita equation are listed in Table 3. The reciprocal of *b* yields a pressure term P_k which is the pressure required to reduce the volume of the powder bed by 50% (Shivanand and Sprockel, 1992). The rank order of the same size fractions of the five heat-treated PEG samples according to the P_k values is as follows: PEG 4000 < PEG 6000 < PEG 8000 < PEG 10000 < PEG 20000. The lower P_k values for PEG 4000 indicate that the material is softer and readily deforms plastically upon compression. It is apparent that the PEG samples having lower molecular weights can deform more readily to fill inter-particulate voids than those with higher molecular weights.

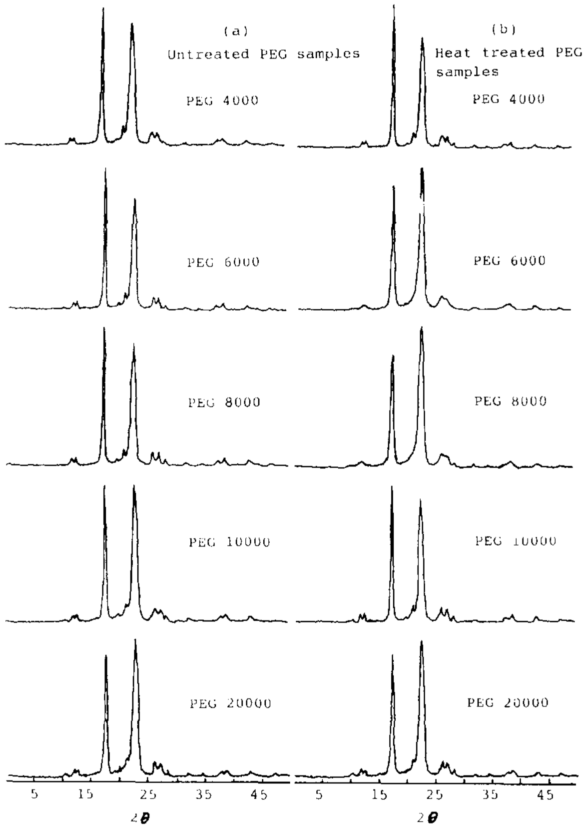

Fig. 1. X-ray patterns of untreated and heat-treated polyethylene glycols. (a) Untreated PEG samples, (b) heat-treated PEG samples.

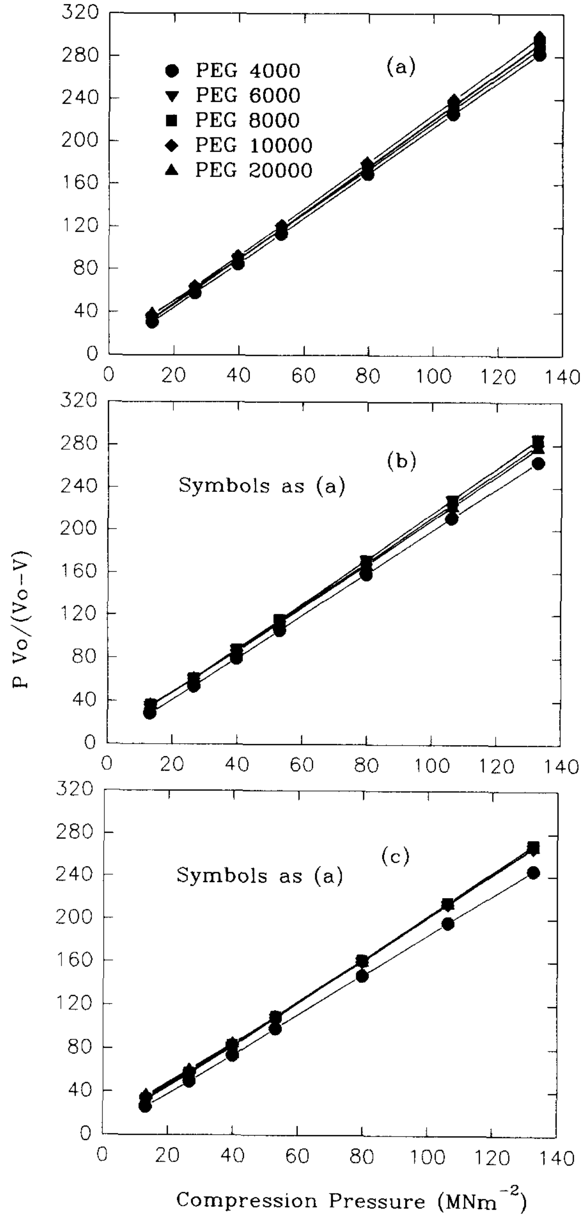

Fig. 2. Kawakita plots for three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–90 μm.

Cooper and Eaton (1962) considered the compaction of powders to take place in two stages: firstly, the filling by particle movement of voids of the same or larger size than the particles, and secondly, the filling of the smaller voids by plastic deformation or fragmentation of the particles. Their equation is:

$$\ln\frac{E_0 - E}{E_0(1 - E)} = a_1\exp\left(\frac{-K_1}{P}\right) + a_2\exp\left(\frac{-K_2}{P}\right) \qquad (3)$$

where E_0 is the initial porosity of the powder bed, E represents the porosity of the compact, and a_1, a_2, K_1 and K_2 are constants.

Fig. 3 shows Cooper-Eaton plots for the five heat-treated PEG samples. The two part linear plot described for a number of materials, e.g., alumina by Cooper and Eaton (1962) was not found in the present study. Single straight lines with higher correlation coefficients were obtained for each of these polymers at pressures ranging from 13.26 to 53.06 MN/m^2. Kurup and Pilpel (1978) have presented an equation for this kind of situation:

$$\ln\frac{E_0 - E}{E_0(1 - E)} = \frac{-Q}{P} + \ln R \qquad (4)$$

where ln R is the intercept on the ordinate and Q denotes the slope. R is equal to the sum of a_1 and a_2 from Eq. 3. Q is the pressure required to induce densification through deformation and can also be used as a measure of the compressibility of the various materials. The rank order of the five heat-treated PEG samples according to the Q values is as follows: PEG 4000 < PEG 6000 < PEG 8000 < PEG 10000 < PEG 20000 (Table 3). This indicates that PEG 4000 is the most compressible polymer, since it undergoes considerable particle plastic deformation at lower pressures. The values of R for all of the PEG samples studied were greater than unity and this would seem to indicate that the compression behavior can be adequately described by plastic deformation.

Compression behavior of powders is readily characterized by Heckel plots (Heckel, 1961). The Heckel equation is expressed as:

$$\ln(1/(1 - D)) = KP + A \qquad (5)$$

where D is the relative density of the compact at pressure P, and K and A are constants. The reciprocal of K is the yield pressure required to induce plastic deformation. The yield pressure (P_y) may be obtained from the linear portion of the plots.

Table 3

Compression parameters of three size fractions of heat-treated polyethylene glycols from Kawakita and Cooper-Eaton plots

Molecular weight	Size fractions	D_i	P_k	r	R	Q	r
PEG 4000	425–250 μm	0.528	0.643	0.999	1.019	1.494	0.991
	250–150 μm	0.494	0.751	0.999	1.019	1.546	0.995
	150–90 μm	0.456	0.608	0.999	1.015	1.251	0.991
PEG 6000	425–250 μm	0.541	1.344	0.999	1.023	2.147	0.996
	250–150 μm	0.526	2.243	0.999	1.061	3.786	0.994
	150–90 μm	0.492	2.226	0.999	1.046	3.341	0.998
PEG 8000	425–250 μm	0.538	1.854	0.999	1.026	2.603	0.999
	250–150 μm	0.524	2.698	0.999	1.066	4.237	0.994
	150–90 μm	0.496	2.513	0.999	1.054	3.761	0.995
PEG 10000	425–250 μm	0.545	2.614	0.999	1.052	3.843	0.995
	250–150 μm	0.514	3.027	0.999	1.061	4.316	0.999
	150–90 μm	0.487	3.376	0.999	1.056	4.379	0.999
PEG 20000	425–250 μm	0.525	3.321	0.999	1.074	4.872	0.993
	250–150 μm	0.507	3.363	0.999	1.063	4.562	0.999
	150–90 μm	0.484	4.326	0.999	1.064	5.181	0.999

D_i, initial relative density of the powder bed; P_k, pressure required to reduce the volume of the powder bed by 50% (MN/m^2); R, total theoretical relative density of the powder bed at infinite pressure for filling voids of the same and smaller dimensions than the particles; Q, pressure required to induce densification through particle rearrangement and deformation (MN/m^2); r, correlation coefficient.

Heckel plots have been classified into three types. Type A and type B were suggested by Hersey and Rees (1971), and type C was proposed by York and Pilpel (1973).

Fig. 4 shows Heckel plots for the five heat-treated PEG samples. The curves show initially steep linear slopes, then level off and coincide at pressures greater than 80 MN/m^2. These polymers obey the Heckel relationship only at lower pressures (not exceeding 80 MN/m^2). The results indicated that densification of these polymers was probably due to plastic deformation and then

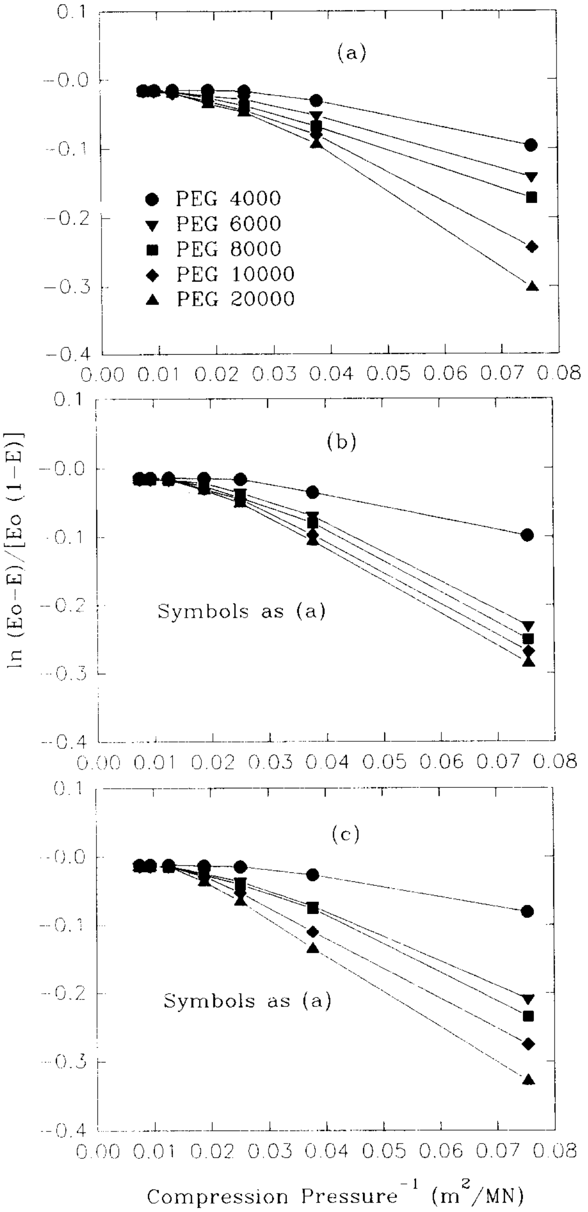

Fig. 3. Cooper-Eaton plots for three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–90 μm.

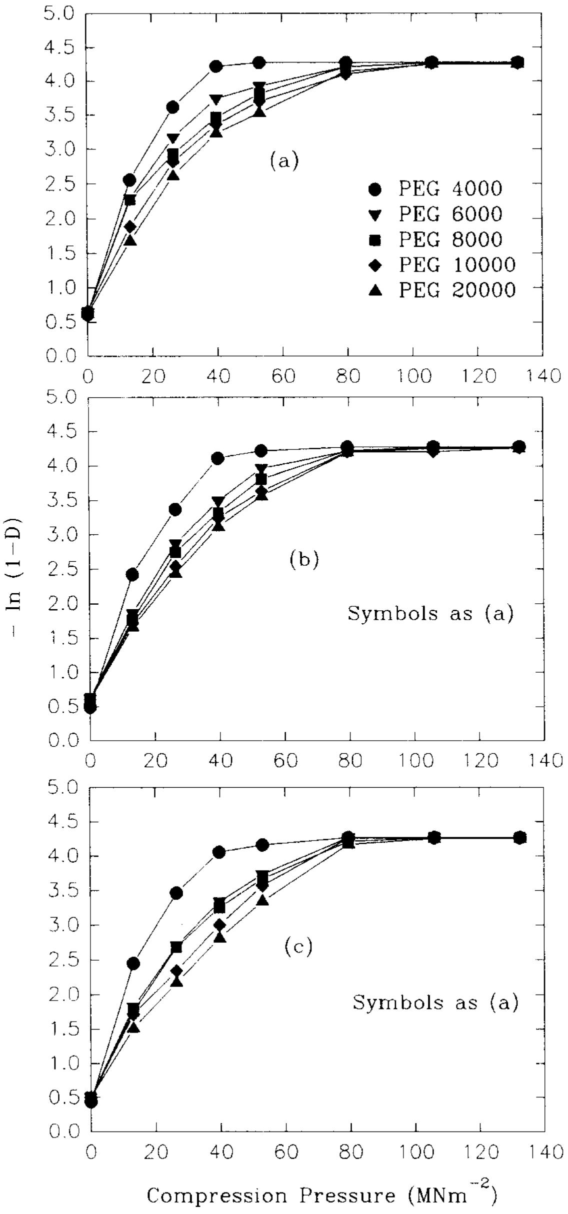

Fig. 4. Heckel plots for three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–90 μm.

asperity melting. However, this compression behavior may be referred to as that of type C.

The values of the yield pressure increase with increase in the molecular weights of the heat-treated polyethylene glycols (Table 4). This indicates that PEG 4000 is the most compressible among all of the polymers studied. The effect of particle size on the yield pressures is very limited. In general, the values of the yield pressure increase with decrease in the particle size of these polymers.

3.5. *Compact surface melting*

The heat-treated PEG molecular weight fractions in this study have a melting range of approx. 59-65°C (Table 1). The melting point demonstrated a non-linear increase with chain length, consistent with the results reported previously by Craig (1990). With the low melting point materials such as the five heat-treated PEG samples, localized melting at the asperities of contact points can easily occur due to a drop in the melting temperature during compression process (Rankell and Higuchi, 1968; York and Pilpel, 1973).

Fassihi (1988) found that the surface of compacts of a polymeric mixture melted at 120 MN/m^2 pressure and completely melted at a critical applied pressure (above 120 MN/m^2). Surface melting of compacts can produce a continuous and transparent film at the edge of the ejected compacts (Fassihi, 1986). In the present study, we also observed a similar phenomenon at pressures greater than 80 MN/m^2. Subsequently, a greater relative density (Fig. 4) and smaller specific surface area (Fig. 5) were obtained for these compacts.

3.6. *Mechanical strength*

During the compression process, surface melting of compacts of the five heat-treated PEG samples may easily occur, resulting in greater particle bonding and tensile strength. Fig. 6 shows the increase in tensile strength of compacts made from the different PEG polymers with increasing compression pressures. It is apparent that the rise in compact tensile strength with pressures is rapid at the lower pressures and moderate at higher pressures. This indicated that the rate of increase in tensile strength with pressure was linked to the predominating mechanism of compression at such pressures. The major compression behavior of the five heat-treated PEG samples is plastic deformation with little rearrangement at lower pressures,

Table 4
Compression parameters of three size fractions of heat-treated polyethylene glycols from Heckel plots

Molecular weight	Size fractions	D_a	D_0	D_b	P_y	r
PEG 4000	425-250 μm	0.622	0.459	0.163	11.198	0.979
	250-150 μm	0.564	0.390	0.174	11.248	0.975
	150-90 μm	0.561	0.356	0.205	11.161	0.968
PEG 6000	425-250 μm	0.607	0.474	0.133	13.065	0.972
	250-150 μm	0.536	0.463	0.073	13.793	0.992
	150-90 μm	0.496	0.397	0.099	14.131	0.991
PEG 8000	425-250 μm	0.593	0.474	0.119	14.308	0.986
	250-150 μm	0.529	0.463	0.066	14.644	0.989
	150-90 μm	0.494	0.403	0.091	14.501	0.986
PEG 10000	425-250 μm	0.563	0.483	0.080	14.728	0.989
	250-150 μm	0.511	0.454	0.057	15.198	0.995
	150-90 μm	0.472	0.397	0.075	16.171	0.993
PEG 20000	425-250 μm	0.516	0.466	0.050	15.158	0.994
	250-150 μm	0.506	0.449	0.057	15.921	0.998
	150-90 μm	0.459	0.398	0.061	17.513	0.996

D_a, densification due to die filling and rearrangement; D_0, relative density of the powder at zero pressure; D_b, densification due to rearrangement; P_y, pressure required to induce plastic deformation; r, correlation coefficient.

which causes a large volume reduction with a small increase in pressure. The rate of increase in tensile strength with pressure is therefore rapid. At higher pressures, asperity melting of the particles and subsequent surface melting of compact become the probable predominant mechanism for volume reduction. Since melting requires a greater energy input and voids left to be filled become fewer, the rate of volume reduction with pressure is smaller. This may explain the lower rate of increase in tensile strength with higher pressures.

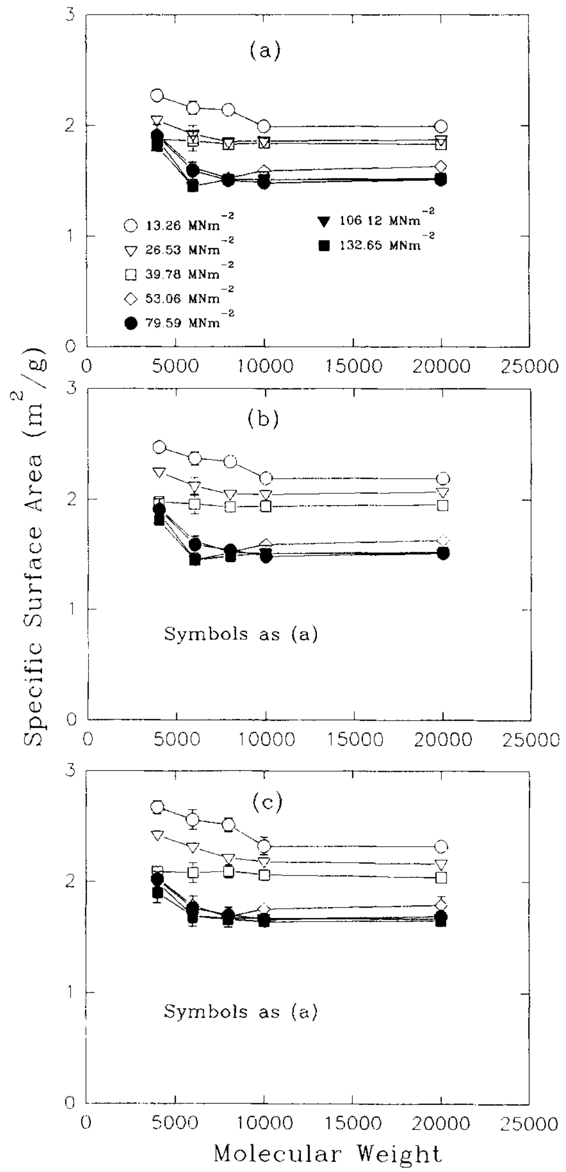

Fig. 5. Relation between compact specific surface area and molecular weight for three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–90 μm.

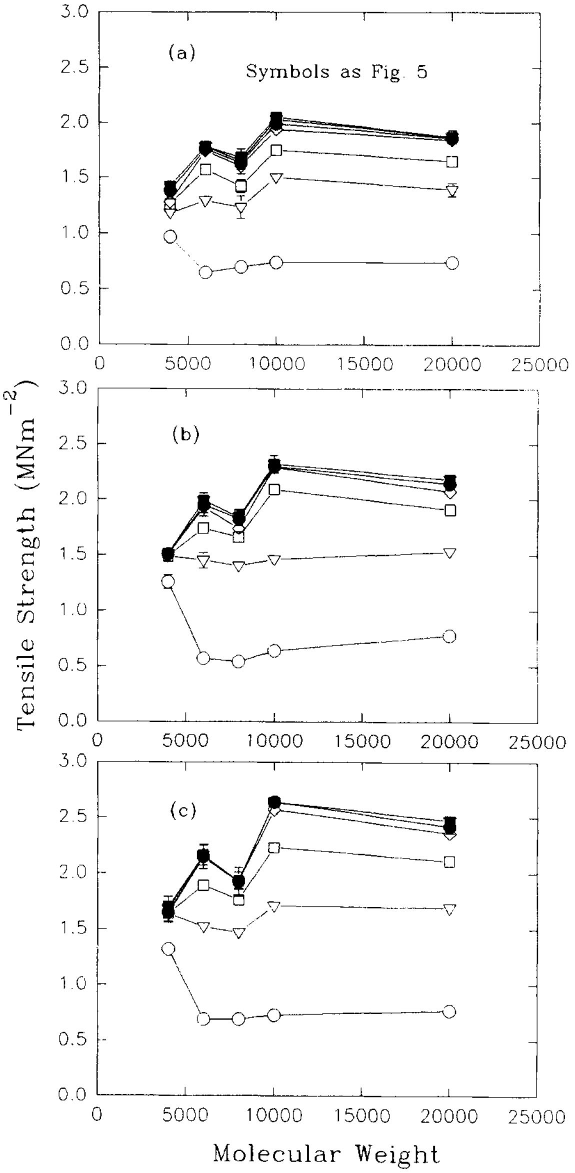

Fig. 6. Relation between compact tensile strength and molecular weight for three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–980 μm.

Fig. 6 displays the relation between compact tensile strength and molecular weight for three size fractions of five heat-treated PEG samples compacted at seven compression pressures. It is evident that PEG 10000 compacts had superior tensile strength compared to the other four polymers at most pressures. The P_k, Q, D_a and P_y values (Tables 3 and 4) indicated that PEG 4000 had superior compressibility when compared to the other PEGs. From Fig. 6 it is obvious, however, that PEG 4000 produced compacts of inferior tensile strength at equal compression pressures. Since PEG 10000 was less compressible than PEG 4000, this demonstrated that the mechanical strength of the compacts was not directly related to the compression mechanism. This could also be attributed to the bonding force of the PEG 4000 particles being inherently weaker than that of PEG 10000 (Al-Angari and Newton, 1985).

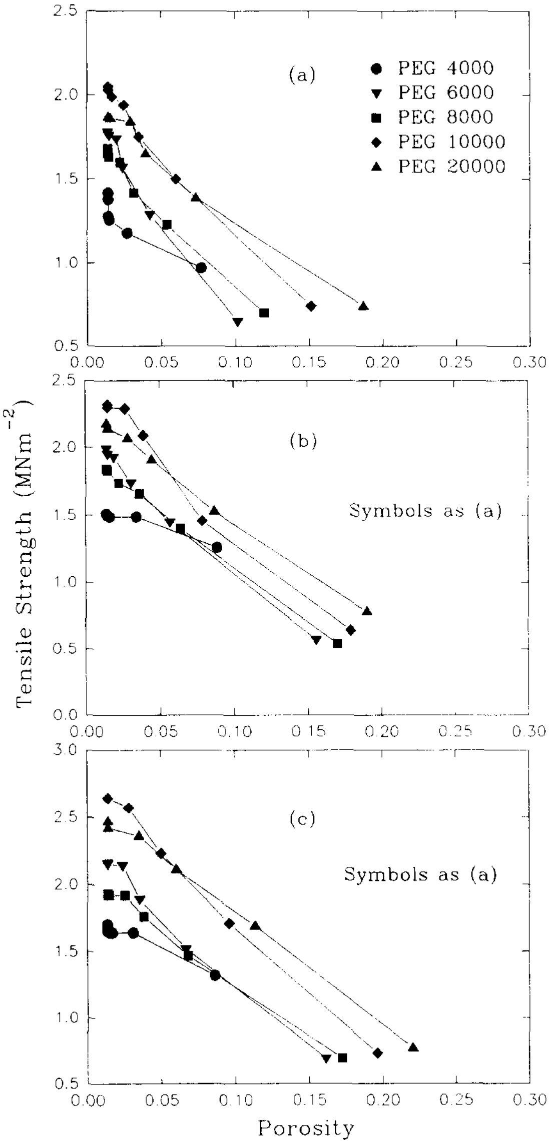

Fig. 7. Effect of porosity on the tensile strength of compacts prepared from three size fractions of heat-treated polyethylene glycols. (a) 425–250 μm, (b) 250–150 μm, (c) 150–90 μm.

Fig. 7 shows that the plots of tensile strength vs porosity are mostly linear. All the heat-treated PEG samples except for PEG 4000 exhibit a steeper slope, indicating that these polymers bond more efficiently at equal porosity. They also converge into a similar profile at lower porosity. This indicated that the mechanism of consolidation in this region was similar. The five heat-treated PEG samples had approximately the same melting point and their inherent tensile strengths were also different, showing that the bonding forces between the particles were of different magnitudes.

4. Conclusions

The results show that there are differences in solid structures between the heat-treated and untreated PEG samples in determining the melting endotherms and X-ray diffraction patterns by using the DSC and X-ray diffractometer, respectively. The peak melting points of the heat-treated polymers increased as the molecular weight increased.

The compression behavior studies showed that PEG 4000 was the easiest of the five polymers to compress. Kawakita, Cooper-Eaton and Heckel methods may be used to distinguish the various compression processes, respectively. At lower pressures all the five polymers obey a simple Heckel equation. However, the compression behavior of the heat-treated PEG samples may be referred to as that of type C from the Heckel plots.

At equal porosity, PEG 10000 compacts had superior tensile strength compared to the other polymers. This could be attributed to the PEG

10 000 particles bonding more readily under compression and probably relatively stronger particle-particle bonding among the five polymers studied.

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References

Al-Angari, A.A. and Newton, J.M., The compaction properties of polyethylene glycols. *J. Pharm. Pharmacol.*, 37 (1985) 151–153.

Cooper, A.R. and Eaton, L.E., Compaction behavior of several ceramic powders. *J. Am. Ceram. Soc.*, 45 (1962) 97–101.

Craig, D.Q.M., Polyethylene glycols and drug release. *Drug Dev. Ind. Pharm.*, 16 (1990) 2501–2526.

Craig, D.Q.M. and Newton J.M., Characterisation of polyethylene glycols using differential scanning calorimetry. *Int. J. Pharm.*, 74 (1991) 33–41.

Fassihi, A.R., Consolidation behavior of polymeric substances in non-disintegrating solid matrices. *Int. J. Pharm.*, 44 (1988) 249–256.

Fassihi, A.R., Continuous matrix formation for controlled drug release: Compression of isotropic polymeric systems. *Int. J. Pharm.*, 34 (1986) 169–172.

Fassihi, A.R., Davies, P.J. and Parker, M.S., Effect of punch pressure on the survival of fungal spores during the preparation of tablets from contaminated raw materials. *Zbl. Pharm.*, 116 (1977) 1267–1271.

Fell, J.T. and Newton, J.M., Determination of tablet strength by the diametral-compression test. *J. Pharm. Sci.*, 59 (1970) 688–691.

Ford, J.L., The current status of solid dispersions. *Pharm. Acta Helv.*, 61 (1986) 69–88.

Heckel, R.W., Density-pressure relationships in powder compaction. *Trans. Metall. Soc. AIME*, 221 (1961) 671–675.

Hersey, J. and Rees J., Deformation of particles during briquetting. *Nature*, 230 (1971) 96.

Kawakita, K. and Ludde, K.H., Some considerations on powder compression equations. *Powder Technol.*, 4 (1970/1971) 61–68.

Kurup, T.R.R. and Pilpel, N., Compression characteristics of pharmaceutical powder mixtures. *Powder Technol.*, 19 (1978) 147–155.

McGinity, J.W., Maincent, P. and Steinfink, H., Crystallinity and dissolution rate of tolbutamide solid dispersions prepared by the melt method. *J. Pharm. Sci.*, 73 (1984) 1441–1444.

Rankell, A.S. and Higuchi, T., Physics of tablet compression: XV. *J. Pharm. Sci.*, 57 (1968) 574–577.

Ravis, W.R. and Chen, C., Dissolution, stability and absorption characteristics of dicumarol in PEG 4000 solid dispersion. *J. Pharm. Sci.*, 70 (1981) 1353–1357.

Shivanand, P. and Sprockel, O.L., Compaction behavior of cellulose polymers. *Powder Technol.*, 69 (1992) 177–184.

York, P. and Pilpel, N., The tensile strength and compression behaviour of lactose, four fatty acids and their mixtures in relation to tableting. *J. Pharm. Pharmacol.*, 25 (1973) 1P–11P.