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Tensile behavior of compressed high-density polyethylene materials

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Abstract

High-density polyethylene (HDPE) materials are widely used in many places in our daily life. These materials are preferred due to their recyclability, product variety, variety of production types, and low cost per unit production. Besides all these features, it is also important that the material can be produced with high mechanical properties by applying different production methods or processes. The investigation of its mechanical properties is becoming also an important issue. In this study, deformation of 1%, 5%, 10%, 15%, 30%, 40%, and 50% ratios were realized by applying a compression process to high-density polyethylene materials. Strip samples were taken out of the compressed samples and subjected to the tensile test process. After the tensile test, the tensile strength values showed differences with increasing deformation rates, and it was observed that the highest value was realized at 10% deformation rate.

Keywords: High-density polyethylene, compression, deformation, tensile test, hardness test

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1. Introduction

Polymers are important materials used in many different fields and industries. They have a wide range of uses from the automotive to the food industry, from the cable industry to chemical and detergent containers, from household and kitchenware to the marine and shipping industry, from the toy industry to the electronics industry, from the packaging industry to the space industry, and from pressure fluid and water pipes to various food containers. These usage areas can be expanded more and more.

When the polymer word is analyzed, poly means multiple, mer means structure, so polymer means multiple structure. Polymers can be classified into three main topics: thermosets, thermoplastics and elastomers [1]. Polyethylene (PE) is a semi-crystalline commercial material in thermoplastic polymers. Besides, polyethylene is a semi-crystalline material obtained by the polymerization of straight-chain hydrocarbons [2]. These hydrocarbons are formed as a result of n repetitions of CH_2 monomers.

HDPE materials are the most used polyethylene materials with a high crystalline rate [3]. HDPE material, which is defined as crystalline or semi-crystalline (with 80% - 90% crystallinity), has a much more regular polymer structure than amorphous polymers. The long and unbranched carbon chains fold to form lamellae called spherulites. Different material particles can be added to semi-crystalline polymers, as well as to crystalline metals. This is done to prevent the dislocation movement in the material and increase the material strength. However, the addition of particulate filler reduces the strength of the material for some polymers. This situation is explained by the fact that the interparticle matrix bond thickness must be less than a certain value. Strength increase is achieved with the addition of appropriate particles in polypropylene (PP) and polyethylene (PE) materials from crystalline polymers [4, 5].

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However, on HDPE material, which has a crystalline structure, dislocations can be prevented by increasing the strain, as in metals. In metals, this can be achieved by traditional methods such as forging and rolling, while it can also be achieved with new methods called severe plastic deformation (SPD), which has some advantages over these [6, 7]. With the effect of the force applied on the material, the polymers become more regular and thus the dislocations are reduced. This situation positively affects the yield and ultimate tensile strength values of the material.

Physically, HDPE materials exhibit both fluidities like liquid and elastic properties like solid together [2]. These two characteristics affect the mechanical properties of HDPE material. It is very important to reveal the mechanical properties of these materials. Mechanical experiments are being done to predict the behavior of materials against static or dynamic loads. These experiments are also performed to see the effect of a process on the material (heat treatment, rolling, forging, etc.) or changes in the material composition (such as alloying) on the material properties. The most frequently used mechanical tests are tensile, compression, hardness, bending, impact, creep, and fatigue tests [3-12].

Akdoğan, 2022, investigated the changes in the mechanical properties of HDPE materials according to the compression state after being subjected to deformation at varying percentages with unidirectional compression. Hardness measurements were made according to the Shore-D hardness test standards and different results were obtained according to the shape change. As a result of the study, the hardness values increase slightly at 10% to 50% compression ratios, while this value decreases at 70% and 80% compression ratios [12].

In this study, different from previous work the changes in the mechanical properties of the HDPE materials were investigated according to the tensile state after being subjected to changing percentages by unidirectional compression.

2. Materials and Methods

In this study, Petkim company's I668 commercial product was used as a granule form. The melt flow rate of HDPE material is 5.5 g/min (190 °C / 2.16 kg). I668 granule raw material is shown in Fig. 1(a). The granules were dried in an oven (Fig. 1(b)) at 60 °C for 4 hours before production to remove moisture from the raw material. Then samples were produced in a 35 mm diameter plastic injection machine with an L/D ratio of 30 by melting at temperatures of 170-180-190-200 °C from the feeding area to the nozzle area. The clamping force of the plastic injection machine is 70 tons. The plastic injection machine is shown in Fig. 1(c). All produced samples were kept in the Nüve TK252 conditioning unit (Fig. 1(d)) at 23 °C and 50% relative humidity for 40 hours according to the ASTM D618 standard. The dimensions of the samples are given in Fig 2. Compression samples were produced by cutting 3±0.2 mm x 13±0.5 mm x 25±0.5 mm size samples as in Fig 2.

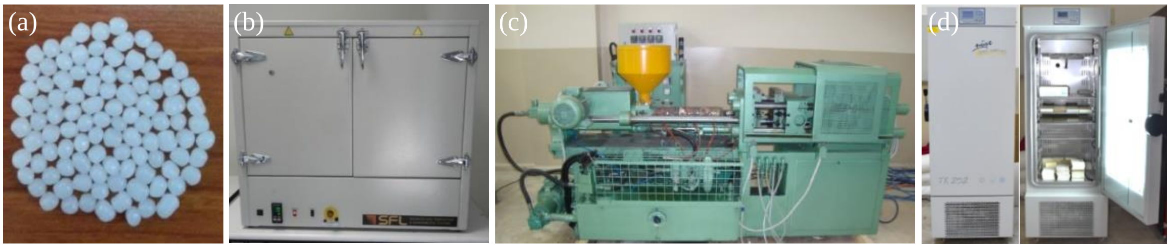

Fig. 1. (a) HDPE granule; (b) oven; (c) plastic injection machine; (d) conditioning unit [12].

3 mm thick materials in the form of flat plates obtained from HDPE were pressed at a constant speed (1.3 mm/min) according to the ASTM D695 standard with a 10% increase in deformation up to 80%. The uncompressed and 80% compressed sample is shown in Fig. 3(a) and Fig. 3(b). The load on the material has been removed, some rebound has occurred due to elastic deformation. After the plastic deformation, which remains constant on the material after this reversal, is measured, it has been observed that it is between 1% and 50%. As a result of this study, changes in hardness values were observed depending on the deformation of the

materials [12]. Tensile test specimens were cut from these flat plate-shaped specimens (Fig. 3(c)). The sizes of the tensile test specimens are approximately 4±0.4 mm x 3.2±1.5 mm x 25±2 mm.

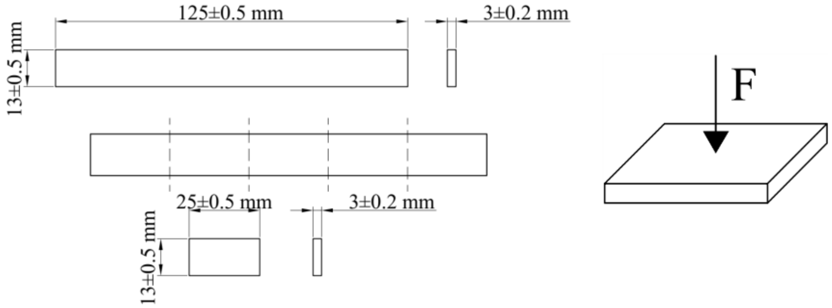

Fig. 2. The dimensions of the compression sample and the direction of compression [12]

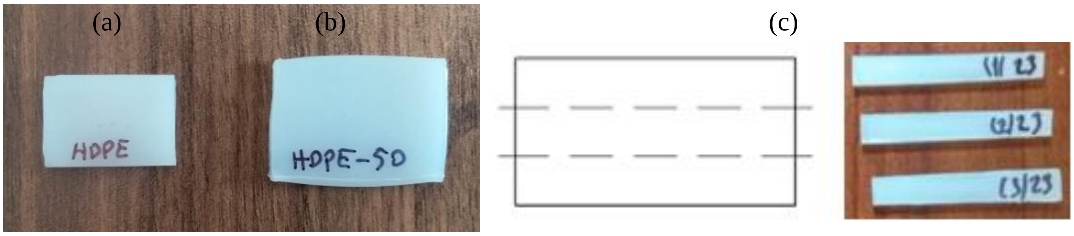

Fig. 3. (a) uncompressed; (b) compressed test specimen; (c) tensile test specimens cut from the specimens

Tensile tests were performed with Shimadzu AGS-X electromechanical tensile tester with 100 kN load cell unit (Fig. 4). The tensile test speed was determined in accordance with the ASTM D638 standard and applied as 50 mm/min. The tests were carried out under room conditions (23 °C and 50% relative humidity). The tensile tests were repeated at least 3 times for each compression state, and the highest, lowest, average and standard deviation values of the results were presented. Plastic deformation rates of compressed HDPE specimens are given in Table 1.

Fig. 4. Shimadzu AGS-X 100 kN universal testing machine [12]

Table 1. Plastic deformation rates of compressed HDPE specimens

Plastic Deformation Rate (%)	0	1	5	10	15	30	40	50

3. Results and Discussions

The tensile graphs of the HDPE samples are given in Fig. 5. It was observed that the elongation at break values increased with increasing compression ratios. Tensile strength, toughness and elongation at break values were calculated. The average (Avg.), maximum (Max.), minimum (Min.) and standard deviation (S.D.) values of the samples were given in Table 2.

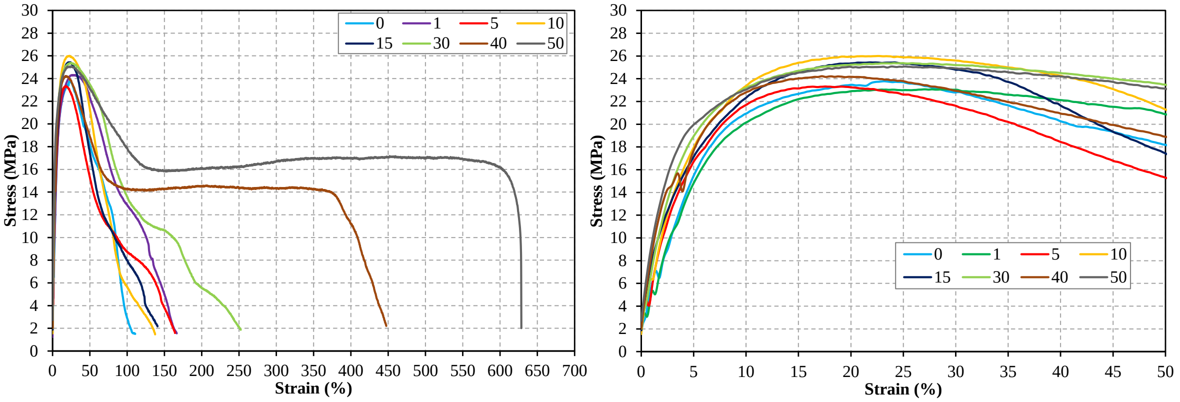

Fig. 5. Stress (MPa) - Strain (%) curves of HDPE materials

In crystalline materials, the dislocation motion is directly related to the deformation of the crystalline regions of the material. Dislocations cause coarse or fine shifts in the polymer, which leads to fragmentation and flow in the crystal structure [16]. Thin slip is defined as a small amount of slip that occurs in many planes. On the other hand, coarse slip is a large amount of slip that occurs in several planes. The yield stress in crystalline polymer materials is determined by the formation of dislocations and their resistance to movement [17].

Table 2. Tensile test results of compressed HDPE materials

Plastic Deformation Rate (%)	Tensile Strength (MPa)				Toughness (J/mm^3)				Elongation at Break (%)			
	Avg.	Max.	Min.	S.D.	Avg.	Max.	Min.	S.D.	Avg.	Max.	Min.	S.D.
0	23.2	23.8	22.6	0.6	1.689	1.921	1.515	0.209	124	133	111	11
1	23.5	24.9	22.5	1.2	2.111	2.462	1.810	0.221	147	167	127	15
5	23.7	24.8	23	1	1.735	1.926	1.627	0.166	143	164	129	18
10	26.4	27.4	25.7	0.9	2.022	2.392	1.769	0.327	138	146	131	8
15	25.3	25.9	24.6	0.9	1.660	1.778	1.558	0.111	116	126	111	8
30	25.3	25.9	24.7	0.6	3.097	3.557	2.439	0.584	255	270	242	14
40	24.4	25	24	0.5	8.387	8.88	7.856	0.513	427	473	379	47
50	25	25.1	24.9	0.1	12.445	13.212	11.909	0.681	627	660	590	35

When the mechanical test results of the materials exposed to compression at different rates are examined, the similarities between the hardness values and the tensile values are remarkable. It is seen that the compression process increases the hardness and tensile values up to a certain extent, then these values decrease (Fig 6). This decrease is related to changes in the crystalline structure of the polymer material matrix. The level at which the dislocation density reaches its maximum level with the effect of compression is the optimum rate for this process. Since the material reaches saturation after this stage, continuing the pressing process causes deterioration in the internal structure and adversely affects the strength and hardness values of the material.

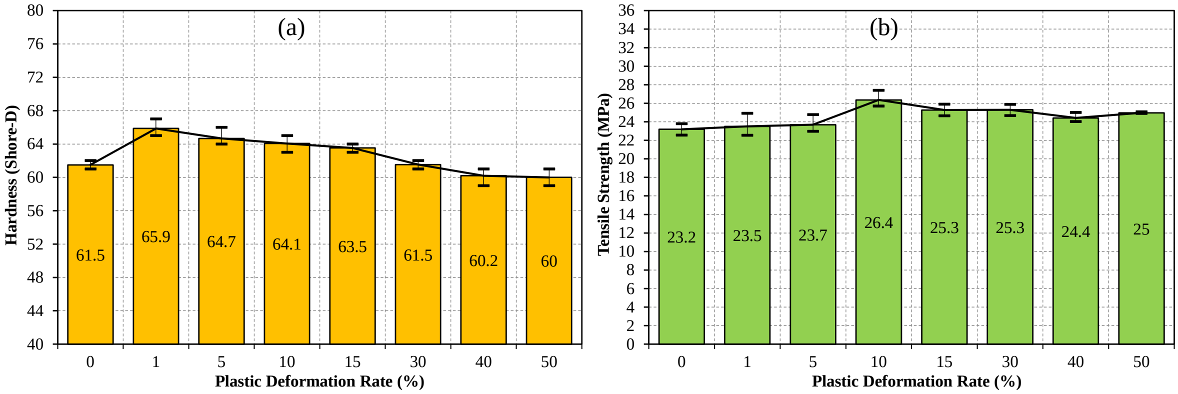

Fig. 6. Comparison of (a) hardness [12]; (b) tensile strength

There is a continuous increase in the toughness values obtained from the stress-strain graphs of the tensile test results, and it is seen that this increase much more after the compression values of 30% (Fig 7(a)). It is seen in Fig 7(b) that this situation is compatible with the elongation at break values. The reason for this can be shown as the deformations that occur in the internal structure of the material with high compression. As a result of the high rate of deformation, the resistance of the dislocations against shear was broken and the situation called coarse slip was realized. This situation, which causes the polymers to slide over each other, has increased the ductility of the material by decreasing the yield strength.

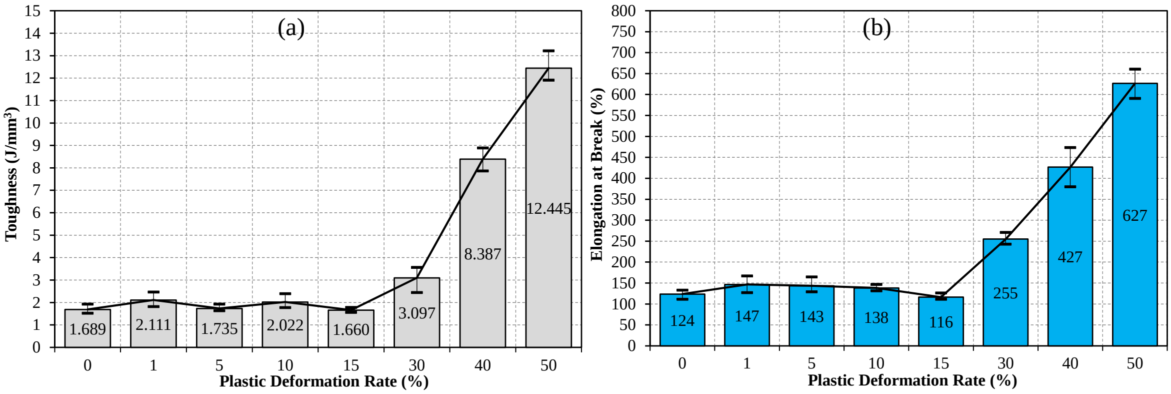

Fig. 7. Comparison of (a) toughness; (b) elongation at break

4. Conclusion

In this study, tensile tests were carried out and compared with the deformations that occur as a result of permanent deformation of HDPE polymer according to the compression state. In general, these materials, elastic deformation and plastic deformation occur as a result of any deformation. Plastic deformation applied up to a certain extent caused an increase in strength in the material with a semi-crystalline internal structure. The most important factors in this increase were explained as the polymer chains becoming more regular as a result of the increase in strain, increasing the dislocation density and preventing the shifts in the internal structure.

As a result of the study, the maximum strength increase in the tensile test was obtained after 10% plastic deformation, and then a partial decrease was observed.

In hardness measurements, the highest value corresponds to 1% deformation. The reason for this can be explained as the surface reaching the optimum strain more quickly as a result of excessive stresses occurring on the material surface after the compression process.

When the tensile and hardness test results are examined, it is seen that the optimum value for the strain rate in this study is 10%. In the case of increasing the deformation, although these values decrease, the toughness values increase as a result of the ductility (elongation at break from 124% to 627%) in the material.

According to the application area of the material, if a high toughness value is desired, it has been shown that the toughness value can be increased approximately 5 times (from 1.689 J/mm^3 to 12.445 J/mm^3) with deformation of up to 50%.

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References

[1] Akdoğan, E. (2019) *Polimer esaslı kompozit malzemelere farklı dolgu maddelerinin ilavesinin mekanik ve ısıl özellikleri üzerine etkilerinin incelenmesi* (Doktora Tezi, Pamukkale Üniversitesi, Denizli). Erişim adresi http://acikerisim.pau.edu.tr:8080/xmlui/handle/11499/26338

[2] Çelikkan, O. (2011) *Yüksek yoğunluklu polietilenin viskoelastik özelliklerinin deneysel incelenmesi* (Yüksek Lisans Tezi, Istanbul Teknik Üniversitesi, İstanbul). Erişim adresi https://polen.itu.edu.tr/items/73743a2e-447c-4213-b568-4faf741cf915

[3] Bartczak, Z., Argon A.S., Weinberg, M. Toughness mechanism in semi-crystalline polymer blends: II. High-density polyethylene toughened with calcium carbonate filler particles. Polymer, 1999. 2347-2365.

[4] Şahbaz, M., & Akdoğan, E. (2022). Yüksek Yoğunluklu Polietilen Malzemelerde Termal Yaşlandırmanın Mekanik Özelliklerine Etkisinin İncelenmesi. Avrupa Bilim ve Teknoloji Dergisi, (34), 757-762.

[5] Bartczak, Z., Morawiec, J. and Galeski, A. 2002. Deformation of High-Density Polyethylene Produced by Rolling with Side Constraints. II. Mechanical Properties of Oriented Bars, Journal of Applied Polymer Science, Vol.86, no.6. p.1405-1412.

[6] Akdoğan, E., & Şahbaz, M. (2022). Çok Yönlü Dövme İşleminin AA5083 Alüminyum Alaşımının Mekanik Özellikleri Üzerindeki Etkisi. Avrupa Bilim ve Teknoloji Dergisi, (34), 739-744.

[7] Öğüt, S., Kaya, H., Kentli, A., Özbeyaz, K., Şahbaz, M., & Uçar, M. (2021). Investigation of Strain Inhomogeneity in Hexa-ECAP Processed AA7075. Archives of Metallurgy and Materials, 66(2), 431-436.

[8] Harekrushna, S., Himanshu, M., Chiranjit, D., Rabiranjan, M. and Sangram, P. 2019. Strain Rate Effects on Tensile Properties of HDPE-PP Composite Prepared by Extrusion and Injection Moulding Method, Materials Sciences and Applications, Vol.10, p.205-215.

[9] Lamri, A., Shirinbayan, M., Pereira, M., Truffault, L., Fitoussi, J., Lamouri, S., Bakir, F. and Tcharkhtchi, A. 2020. Effects of Strain Rate and Temperature on the Mechanical Behavior of High-Density Polyethylene, Journal of Applied Polymer Science, Vol.137, no.23. pp.48778.

[10] Koriem, A., Ollick, A.M. and Elhadary, M. 2021. The Effect of Artificial Weathering and Hardening on Mechanical Properties of HDPE with and without UV Stabilizers, Alexandria Engineering Journal, Vol.60, p.4167-4175.

[11] Nitta, K. H., & Maeda, H. (2010). Creep behavior of high density polyethylene under a constant true stress. Polymer Testing, 29(1), 60-65.

[12] Akdoğan, E. (2022). Investigation of the Effects of Unidirectional Compression on the Hardness of High-Density Polyethylene Materials. Open Journal of Nano, 7 (2), 94-103. DOI: 10.56171/ojn.1110326

[13] Standard Practice for Conditioning Plastics for Testing, ASTM Std. D618, 2013.

[14] Standard Test Method for Tensile Properties of Plastics, ASTM Std. D638, 2017.

[15] Standard Test Method for Compressive Properties of Rigid Plastics, ASTM Std. D695, 2016.

[16] Pawlak, A., Galeski A,. Rozanski, A. Cavitation during deformation of semicrystalline polymers. Progress in Polymer Science. (2014). 921-958.

[17] Bowden, P.B., Young, R.J. Deformation Mechanisms in Crystalline Polymers. Journal of Materials Science. (1974), 2034-2051.