Enhanced Tensile Properties of Stone Wool Fiber-Reinforced High Density Polyethylene (HDPE) Composites

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In this study, a mineral fiber composite of stone wool-reinforced high density polyethylene (HDPE) with different weight percentages was tested. For preparation of the samples a hot pressing technique was used. Significant improvement of the tensile strength was observed for composites of stone wool HDPE with a fiber content of 20 wt-%. The fracture surfaces of the samples were analyzed for their inter layer bounding by scanning electron microscopy (SEM).

Worldwide interest in natural fibers has increased due to their low cost, low density, high hardness, good thermal resistance, and their respective environmental friendliness [1-3]. The use of natural fibers as reinforcement for thermoplastics is desirable, since it is based on abundant resources. One of these fibers is stone wool fiber. Stone wool fiber is a natural mineral fiber which is produced by spinning the stone into a wool form at a temperature of about 1600 °C followed by stream of air or steam. HDPE is a type of polyethylene thermoplastic which has a low degree of branching and thus has stronger intermolecular forces that provide a high tensile strength.

The tensile test represents a fundamental material mechanical engineering test, where a sample is subjected to uniaxial loading. The results obtained from tensile tests are usually used for selecting a material for engineering applications, and for principal predicting how the material reacts under tension load.

In the literature, there are several studies concerning the utilization of fibers or particles as reinforcement in composites of HDPE. Homaeigohar et al. [4] studied the effects of particle size and volume fraction of tri-calcium phosphate to the mechanical properties of the tri-calcium phosphate-high density polyethylene (β-TCP/HDPE) composite. It was observed that an increase of the β-TCP content in composite will increase its modulus of elasticity. However, when larger β-TCP particles were used in the preparation of the composite, a lesser increase in elasticity modulus was found. Besides, according to the study of Gungor [5], iron (Fe) filled polymer composites showed lower yield strength and lower percentage of elongation. Meanwhile, the modulus of elasticity of the composites is higher than those of HDPE.

The tensile strength of zinc powder filled HDPE composites decreased as the volume fraction of the zinc powder increased while incorporation of wheat straw into HDPE gave higher values of tensile strength as compared to the cornstalk and corncob [6, 7]. The highest value of tensile strength was achieved in the composite containing 20 % of piassava fibers and the elasticity modulus of composites increased with the fiber content what was discovered by Suarez and Elzubair [3]. In addition, Araujo et al. [8] also found in their study of high performance formulation in HDPE composites reinforced with curauá fibre that there was a large increase in tensile strength with the addition of 20 wt.-% curauá fiber.

Based on the above mentioned facts, the potential of HDPE as a matrix in composites seem promising. In this study, waste stone wool fibers gathered from production floor are proposed as fiber material that will reinforce HDPE. The study is thus investigating the tensile properties of stone wool-reinforced HDPE composites and their fracture surfaces after tensile testing by using scanning electron microscopy (SEM).

Materials and Methods

Materials. The HDPE used in this study was in pellet form. In order to dry out the moisture of the HDPE pellet, it was spread evenly on an aluminium foil and dried in the Memmert drying oven for 24 hours at 70 °C constantly. Furthermore, the stone wool fibers were provided by one of the established rock wool industry in Malaysia, where the waste of caking process is sacrificed for the investigation.

Fiber Treatment. Stone wool fibers which were used as filler was prepared carefully according to the method of Joseph et al. [9], where the fiber was cleaned by ultrasonic cleaner using distilled water for 90 min in order to remove the wax as well as impurities that present in the micro composition of the wool. Water content of the stone wool was then wringed out, and the stone wool was dried in the LabTech vacuum drying oven for 8 hours at constant temperature of 105 °C. This step was carried out to ensure the entire stone wool used in this investigation has constant density by drying out the trapped moist inside stone wool so that the bonding could take place in a steady state.

Preparation Method of Composites. The weighed matrix and filler were mixed together by the Haake Polymer Lab OS Rheodrive 16 internal mixer. The processing temperature was 165 °C with rotor speed of 50 rpm. The duration of mixing process was 10 min, where at the beginning stage the matrix was put into the mixer within 30 seconds after the rotor started rotating, to allow the matrix melt for the initial 5 min. Then, after the remaining filler was added into the filler, both matrix and filler were mixed together uniformly for a period of 5 min. The mixture of matrix and filler has become batches of post mixing materials after such process. The post mixing batches were then hot pressed by using the motorise hydraulic hot moulding machine (Go Tech Testing Machine Inc., Taiwan) to form composite sheets of different weight ratios. They were first melted in the hot moulding machine within 10 min where the mould assembly slightly touched the upper mould of the hot moulding machine, no pressure is applied during this step.

After they were fully melted, a constant hot pressing for 10 min was uniformly applied to hot press the mixed material. The pressure of this step was gradually raised from 0 kg/cm³ to 70 kg/cm³ to squeeze out possibly formed air bubbles. Upon completion of hot pressing, the mold assembly was taken out and put into the lower press plate of the hot molding machine for cooling to the level of room temperature for 10 min and no pressure was applied during this step. The mold assembly was then taken out and the composite sheet was removed from the mold cavity. Thereafter, the composite sheets of each weight ratios were then profiled according to ASTM standard of test specimen.

A total of 15 specimens were manufactured in order to complete the investigation. Composites formulations in filler weight percentage [wt.-%] is presented in Table 2.

Rock	Percentage (wt.-%)
basalt	58 - 80
dolomite	10 - 30
briquette	0 - 40
limestone	0 - 5
coke	13.5

Table 1. Stone wool composition (wt.-%)

Filler weight ratio (wt.-%)	Filler (g)	Matrix (g)
0	0	280.358
10	3.428	126.163
20	6.496	112.144
30	9.740	98.126
40	12.987	84.108

Table 2. Composite formulations in weight percentage (wt.-%)

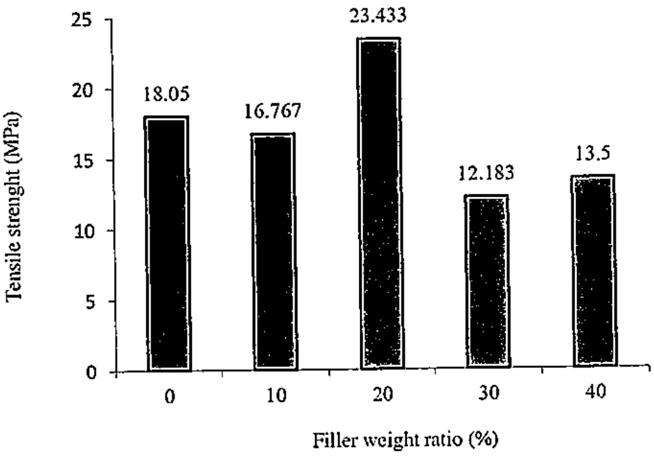

Figure 1. Variation of tensile strength of stone wool-reinforced HDPE composites with filler weight ratio

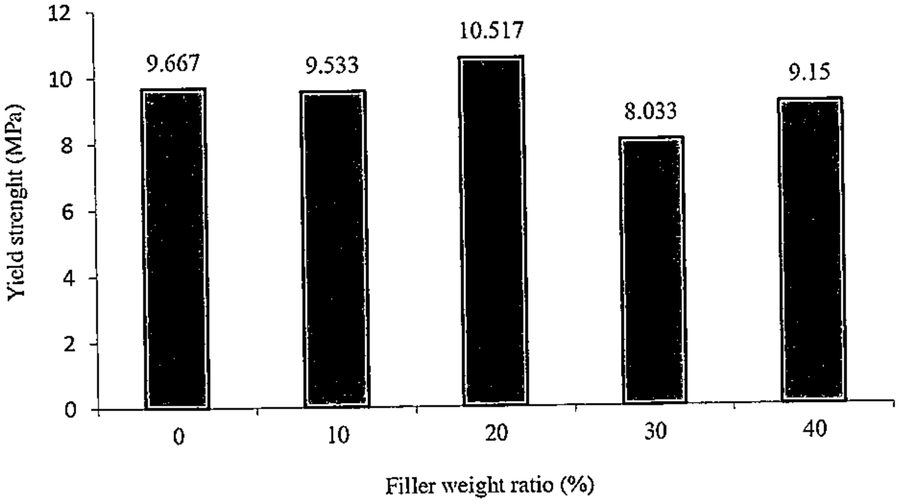

Figure 2. Yield strength of investigated stone wool-reinforced HDPE composites dependent on the filler weight ratio

Results and Discussion

Tensile Strength. Figure 1 represents the tensile behaviour of stone wool-reinforced HDPE with filler to matrix weight ratios between 0 % to 40 %. The tensile test was conducted according to ASTM D3039 using a universal testing machine (Shimadzu AG-1 100KN, Japan) at room temperature, where the crosshead speed was set at 2 mm/min and a load cell capacity of 100 kN was applied to the specimen.

Table 3 shows that the 20 wt.-% stone wool-reinforced HDPE composite has the highest tensile strength compared to pure HDPE. It is interesting to note that the interfacial strength between 20 wt.-% of stone wool reinforcement and 80 wt.-% of HDPE matrix is the strongest which resulted in the highest tensile strength. As for mathematical modeling, the parameters employed to predict the tensile strength of HDPE-reinforced with variety of natural fibers including stone wool were derived as:

$$\sigma_{IU} = \sigma_{IF}\left(1-\frac{l_c}{2l}\right)V_F + \sigma_M^{*}(1-V_F), l \geq l_c \quad (1)$$

The modified equation for cylindrical fibers was

$$\sigma_{IU} = \alpha\tau_i V_F \frac{l}{d} + \sigma_M^{*}(1-V_F), l \leq l_c \quad (2)$$

The modified equation for rectangular fibers was

$$\sigma_{IU} = \alpha\tau_i\left(\frac{1}{2}\right)\left(\frac{W+T}{WT}\right) + \sigma_M^{*}(1-V_F), l \leq l_c \quad (3)$$

with σ_{IU}: compile tensile strength, σ_{FU}: interfacial shear strength, σ^{*}_{M}: maximum stress evaluated at the peak composite strength, l: fiber length, l_c: critical fibre length, V_F: fiber volume fraction, d: cylindrical fiber diameter, α: clustering parameter, W: rectangular fiber width, T: rectangular fiber thickness [12].

Yield Strength. Table 4 and Figure 2 reveal the pattern of yield strength for the tested specimens with different set of filler-matrix composition. It can be seen that the 20 wt.-% stone wool-reinforced HDPE composite has the highest yield strength as compared to all other different weight ratios tested. The highest value of yield strength was 8.79 % higher than for pure HDPE. It is significant that the 20 wt.-% stone wool-reinforced HDPE composite has the greatest performance with respect to the strength values. Materials with high yield strength are significantly important especially at the design stage which involves materials selection, helping the engineer to understand at which stress level the material can withstand the forces before plastic deformation takes place.

Ductility. Results in Figure 4 together with tabulated findings in Table 6 show that pure HDPE has the highest ductility, since it has the highest elongation [%] which is 28.7 %. Both the 20 wt.-% and 10 wt.-% stone wool-reinforced HDPE composites are moderately ductile among all composite specimens, where their elongation is 17.6 % and 16.0 %, respectively. The values for the 30 wt.-% and the 40 wt.-% stone wool-reinforced HDPE composites are 5.5 % and 2.9 %, respectively. Both the 30 wt.-% and 40 wt.-% reinforced stone wools experience little plastic deformation before fractures take place. Presence of tiny air bubbles in the 30 wt.-% and the 40 wt.-% stone wool-reinforced HDPE might be a contributing factor for a low elongation [%] which eventually form a crack towards final fracture with little plastic deformation.

For specimens such as 10 wt.-% and 20 wt.-% stone wool-reinforced HDPE composites, it can be explained that there was an extensive plastic deformation in the vicinity of the advancing cracking, and the process proceeds relatively slow. Stone wool

Filler weight ratio (wt.-%)	Tensile stregth (MPa)
0	18.05
10	16.767
20	23.433
30	12.183
40	13.5

Table 3. Tensile Strength of stone wool-reinforced HDPE with different weight ratios

Filler weight ratio (wt.-%)	Yield strength (MPa)
0	9.667
10	9.533
20	10.517
30	8.033
40	9.150

Table 4. Yield strength of stone wool-reinforced HDPE with their respective weight rations

Filler weight ratio (wt.-%)	Elasticity modulus (GPa)
0	0.508
10	0.477
20	0.817
30	0.295
40	0.381

Table 5. Elasticity modulus of stone wool-reinforced HDPE with different weight ratios

Filler weight ratio (wt.-%)	Elongation (%)
0	28.7
10	16.0
20	17.6
30	5.5
40	2.9

Table 6. Elongation of stone wool-reinforced HDPE with different weight ratios

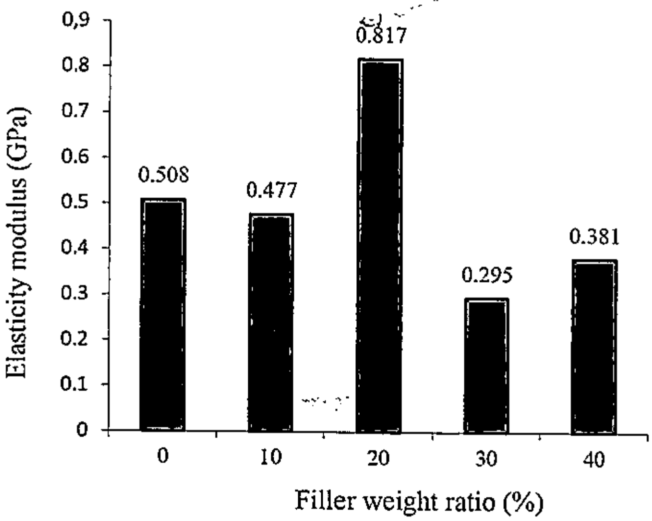

Figure 3. Elasticity Modulus of the various ratio stone wool-reinforced HDPE composites

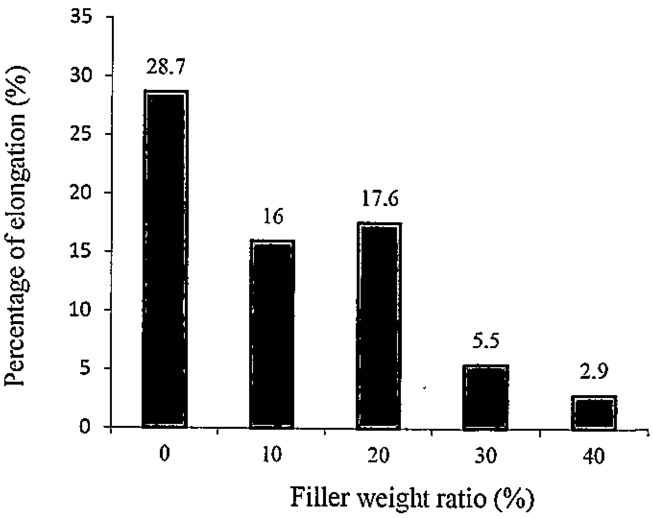

Figure 4. Elongation of the various stone wool-reinforced HDPE composites

does not act as a good reinforcement for HDPE matrix in term of ductility, what can be drawn from the fact that pure HDPE has the highest elongation value. On the other hand, even though stone wool fiber as filler material does not contribute an increase of the ductility as compared to pure HDPE, it has a positive impact as it provides resistance to the ductility what is desired for most engineering application materials.

Micrographic Observations. From the morphology study, the 10 wt.-% stone wool-reinforced HDPE composite (Figure 5) exhibited the typical fracture surface of the 10 wt.-% stone wool loaded tensile specimens. A ductile failure can be observed in the matrix region. It can be clearly seen that the wedges are long and pulled away (separated) from the surrounding matrix. Wedging is one of the modes of deformation in polyethylene. Moreover, in Figure 6 it can be seen that the stone wool tensile specimen with 40 wt.-% is loaded with wedges and air bubbles on the fracture surface of the specimen correlating with a ductile fracture phenomenon. However, the specimen undergoes relatively little plastic deformation as compared to that of the 10 wt.-% stone wool loaded specimen. It can be explained by the presence of the air bubble on the surface of the 40 wt.-% stone wool loaded specimen, where air bubbles represent one of the factors that form a crack towards fracture with little deformation.

Conclusions

A stone wool-reinforced high density polyethylene (HDPE) was prepared with varying weight percentage. The variation of tensile, yield, elasticity modulus, and elongation percentage of stone wool-reinforced HDPE composites have been investigated as a function of fiber weight percentages. The results show that the tensile properties of the 20 wt.-% stone wool fiber are efficient in improving the reinforcement effect in the HDPE matrix. Therefore, the potential of stone wool is highlighted with respect to good mechanical properties in combination with the HDPE composite production.

Figure 5. SEM micrograph of a specimen with 10 wt.-% stone wool fiber content

Figure 6. SEM micrograph of a specimen with 40 wt.-% stone wool fiber content

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Abstract

Verbesserte mechanische Eigenschaften von steinwollefaserverstärkten Hartpolyethylen-Kompositen. In der diesem Beitrag zugrunde liegenden Studie wurde ein Mineralfaserkomposit aus einem mit verschiedenen Prozentsätzen steinwolleverstärkten Hartfaserpolyethylen (high density polyethylene (HDPE)) untersucht. Zur Probenvorbereitung wurde eine Heißpresstechnik eingesetzt. Es wurde eine signifikante Verbesserung der Festigkeit der Komposite aus Steinwolle-HDPE für einen Faseranteil von 20 gew.-% beobachtet. Die Oberflächen der Probenbruchstellen wurden mittels Rasterelektronenmikroskop (REM) hinsichtlich ihrer Zwischenlagenbindung analysiert.

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