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Investigation of the mechanical characteristics of composites based on CFA and rLDPE

Prinob Aksar[1], Minson Simatupang[2], Sudarsono[1], Endro Sukotjo[3], Al Ichlas Imran[1], Aditya Rachman[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Halu Oleo University, 93232 Kendari, Indonesia
[2]Department of Civil Engineering, Faculty of Engineering, Halu Oleo University, 93232 Kendari, Indonesia
[3]Department of Management, Faculty of Business and Economics, Halu Oleo University, 93232 Kendari, Indonesia

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The effect of coal fly ash (CFA) as a filler in recycled low-density polyethylene (rLDPE) matrix composites on the compressive strength, flexural strength and flexural modulus of this material was investigated. The composites were prepared by blending CFA and rLDPE at levels of 20 wt%, 30 wt% and 40 wt% CFA with 80 wt%, 70 wt% and 60 wt% rLDPE. Mixing was carried out at 160 °C until the rLDPE melted, then CFA was added and mixed until homogeneous. The mixture was then poured into a mold and subjected to direct molding. Compressive strength tests were performed according to ASTM D695 and flexural strength tests according to ASTM D790-03. SEM analysis was used to characterize the microstructure of the composite. The results showed that the composite with 20 wt% CFA and 80 wt% rLDPE provided the highest compressive and flexural strength of 9.60 MPa and 16 MPa, while higher proportion of CFA reduced the compressive strength. SEM analysis shows that good distribution of CFA in rLDPE matrix improves the mechanical properties of the composite.

Keywords: coal fly ash, recycled LDPE, polymer composite, compressive strength, microstructure analysis, bending strength, elasticity modulus.

Дослідження механічних характеристик композитів на основі CFA та rLDPE. ***Prinob Aksar, Minson Simatupang, Sudarsono, Endro Sukotjo, Al Ichlas Imran, Aditya Rachman***

Досліджено вплив вугільної летючої золи (CFA) як наповнювача в композитах з матрицею з переробленого поліетилену низької щільності (rLDPE) на міцність при стисканні, міцність на згин і модуль пружності при згинанні цього матеріалу. Композити були виготовлені шляхом змішування CFA та rLDPE в обсягах 20 мас.%, 30 мас.% та 40 мас.% CFA, 80 мас.%, 70 мас.% та 60 мас.% rLDPE. Процес змішування проводився при температурі 160 °C до розплавлення rLDPE, потім додавали CFA і перемішували до однорідності. Після цього суміш заливалася у форму та пресувалася під тиском. Були проведені випробування на визначення міцності на стиск за стандартом ASTM D695 та міцності на вигин за стандартом ASTM D790-03. Для визначення мікроструктури композиту проводили аналіз SEM. Результати показали, що композит з часткою 20 мас.% CFA і 80 мас.% rLDPE забезпечував найвищу міцність на стиск та вигин 9,60 МПа та 16 МПа, тоді як більш висока частка CFA знижувала міцність на стиск. Аналіз SEM показує, що хороший розподіл CFA у матриці rLDPE покращує механічні характеристики композиту.

1. Introduction

Coal fly ash (CFA) is a material that has the potential to be a reinforcing element in a composite material. CFA, a waste product from the combustion of coal used in steam power plants, contains silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO), and iron oxide (Fe_2O_3). These elements can improve the mechanical properties of a material for example in the production of concrete [1]. The use of coal as one of the main energy sources in power plants causes a significant increase in the production of coal waste [2]. Meanwhile, low-density polyethylene (LDPE) is a type of thermoplastic polymer material that is lightweight, flexible, and chemically resistant. In addition, LDPE is resistant to low temperatures and pressure, so this type of plastic is known for its unique properties. [3].

LDPE is widely used as disposable packaging. Of course, this is one of the types of waste, the volume of which will increase significantly every year. In the field of composite materials, efforts are being made to improve waste utilization efficiency and sustainability in the development of materials based on them. Utilizing coal ash waste as a filler in bituminous materials can increase the mechanical performance and service life of the material [3]. This shows that coal ash waste can act as an effective filler material in LDPE based composites, namely, it can improve the mechanical properties and performance of the material in various applications. In addition, various combinations of recycled fibers and fillers can influence the mechanical properties and energy absorption of the fiber-reinforced composite panel [5].

This research is very relevant in the context of developing a composite material made from LDPE reinforced with coal ash, where variations in filler proportions can increase the required mechanical properties. Apart from that, this research can explore the potential of combining coal ash and LDPE waste to produce composite materials that are stronger and more environmentally friendly. In addition, the use of waste as raw material in making composites is in line with circular economy principles, where waste is seen as a resource that can be reused. Using industrial waste as raw material in composite production not only reduces waste, but can also reduce dependence on virgin raw materials [6]. The blending of low-density polyethylene (LDPE) and polyethylene terephthalate (PET) waste with a polyester resin matrix affects the tensile strength and microstructure. Testing of a blend of high-density polyethylene (LDPE) and low-density polyethylene (LDPE) fibers according to ASTM D368-14 showed an increase in the tensile strength of the composite [7].

Other studies also show that composites containing 3 wt.% fly ash and 5 wt.% SiC has higher compression strength, therefore, to improve mechanical properties, uniform distribution of the filler in the composite material is necessary [8]. Based on the information obtained and the potential of coal ash and low-density polyethylene waste, further research is needed to utilize these two wastes to produce a composite material that can meet industrial needs and contribute to emission reduction.

2. Experimental

In preparing materials for composite production, LDPE waste is first crushed into small pieces of 10-50 mm using an Andaro brand shredder, then cleaned of dirt stuck to the surface in several stages, including soaking in a plastic container for 24 hours at room temperature to facilitate the dirt removal process. Then mechanical processing is carried out manually for 5 minutes. After this, rinsing with clean running water is carried out; and the final stage is the drying process using a vacuum oven at a temperature of 40 °C for 24 hours. Meanwhile, fly ash is filtered using a 100 mesh filter and dried using a vacuum oven at 40 °C for 24 hours to reduce water content.

Composites of fly ash and LDPE waste were prepared with the component ratios of 20, 30 and 40 wt% for coal ash waste and 80, 70 and 60 wt% for LDPE. The available LDPE waste pieces are placed in a metal container at a temperature of 160 °C and left for 15 minutes until they turn into liquid. After this, coal ash is added to the melted HDPE waste by mechanical mixing for 10 minutes until a homogeneous mixture is obtained. The homogeneous composite material mixture is then poured into a 40 x 40 x 40 mm mould, which is lined with aluminium foil to facilitate removal, and subjected to a 5 kg load for 1 hour at room temperature until the material hardens; after which it is opened for the next procedure. For compressive and bending strength tests, 5 samples of each composition were prepared to ensure better statistical analysis. In addition, tests were performed multiple times for each composition to ensure consistency of results and to calculate standard deviations of compressive and flexural strength.

Compressive strength tests and scanning electron microscopy

The compressive strength test of the material is carried out according to ASTM D695 using a 40 × 40 × 40 mm cube-shaped specimen. A universal testing machine of the MBT brand with a lifting capacity of 100 kN and an accuracy of 0.338 kN was used. The compressive strength of composite materials was calculated using the equation:

$$\sigma = \frac{F_{\max}}{A} \quad (1)$$

where σ is the compressive strength (Kg/mm² or MPa); F_{max} is the applied compressive load (N); A is the surface area (mm²).

A scanning electron microscopy (SEM) study was conducted to characterize the microstructural surface/morphology of micron-sized inorganic and organic materials based on CFA and rLDPE composite materials. The equipment used was Vega3 lmu Tescan, Czech. The specimens used in the SEM were previously tested for compressive strength and had the shape of a cube measuring 5 × 5 ×5 mm. SEM specimens were first prepared by cutting with an electric grinder and then dried for dehydration using a graded ethanol solution. The specimen was placed on the SEM stage using a conductive adhesive made of carbon tape and then subjected to a coating process using metallic gold. After coating, the specimen was left for 24 hours before being examined by SEM with the following mode: magnification 2.00 kX, field of view 69.8 µm, working distance 14.37 mm, speed 4, beam current 1 nA, SE detector, energy 20 keV and HighVac pressure.

Bending strength and modulus of elasticity

The test was carried out to determine the bending strength of the composite material. A universal material testing instrument with the Three-Point Bending test type was used. According to ASTM D790-03, with a specimen size of 200 × 50 × 10 mm, the following equation is used:]

$$\sigma = \frac{3Fl}{2bd^2} \quad (2)$$

where, l is the length (mm); b is the width (mm); d is the thickness (mm); F is the force (N); σ is the bending stress (N/mm^2).

The compressive strength test results and SEM data were then used to determine the relationship between CFA (20 wt%, 30 wt%, and 40 wt%) and rLDPE (80 wt%, 70 wt%, and 60 wt%, respectively) contents and compressive strength as well as material microstructure. This analysis was aimed at obtaining the best composition for the production of materials from CFA and rLDPE.

3. Results and discussion

Compressive strength and scanning electron microscopy

Table 1 presents the results of compressive strength tests of CFA/rLDPE composite materials, indicating the composition that effectively withstands the compressive load during testing.

Table 1 shows the compressive strength values of CFA-reinforced rLDPE composite materials with compositions of 0 wt. %, 20 wt. %, 30 wt. % and 40 wt. % CFA. The results showed that the compressive strength of pure 100 wt% LDPE was 13.3 MPa, while a decrease in strength was observed with the addition of 20 wt%, 30 wt% and 40 wt% CFA. This decrease was due to the weak interaction between rLDPE and CFA, since the addition of CFA resulted in the formation of a inhomogeneous structure in the rLDPE matrix. The inhomogeneous structure and reduced polymer adhesion lead to the formation of voids, which can reduce the bond strength of the material [9].

On the other hand, the composition of 20 wt.% CFA showed the highest compressive strength value of 9.60 MPa compared to the composition with 30 wt.% CFA (9.23 MPa) and 40 wt.% CFA (8.67 MPa). This is due to the fact that the addition of CFA in the proportion of 30 wt.% and 40 wt.% resulted in the formation of a more heterogeneous structure in the mixture, which led to a decrease in strength [5].

The results in Table 1 show that the characteristics of each material play an important role in the final result. rLDPE, as a polymer matrix, has lower mechanical strength than mineral-based CFA. This leads to a decrease in compressive strength when the proportion of CFA in the mixture increases. The mechanical properties of rLDPE do not contribute to the improvement of the compressive strength of the material, especially when the volume of CFA is larger compared to rLDPE.[10]. Moreover, another study also shows that adding fly ash to concrete mix can reduce the compressive strength, especially if its proportion exceeds a certain limit [11]. Material compatibility in composites is very important, as the presence of weaker materials can affect structural integ-

Table 1: Compressive Strength Test Results

Sample Types	Weight of CFA (%)	Weight of rLDPE (%)	σ (MPa)
Sample (Control)	0	100	13,3
Sample A	20	80	9.60
Sample B	30	70	9.23
Sample c	40	60	8.67

rity. The interactions between different materials in a composite can affect the overall mechanical performance [10][12].

The distribution of particles in the mixture also plays an important role in compressive strength. Uneven distribution can cause the formation of voids or porosity in the composite material, which has a negative impact on its ability to withstand compressive loads. Optimal particle distribution is essential to achieve the desired compressive strength [13]. The higher volume of rLDPE in the blend may affect the interfacial bonds between the different materials, which will affect the mechanical properties of the composite. Changes in mixture density also affect compressive strength. As the volume of rLDPE increases, the overall density of the composite tends to decrease, resulting in a decrease in the material's ability to withstand compressive forces. This decrease in density is the main factor in reducing compressive strength, because denser materials generally have better mechanical properties [10][14].

In this study, the ratio of 20 wt.% CFA in 80 wt.% rLDPE is considered as the optimal composition that not only balances the mechanical properties of both materials, but also ensures adequate load distribution and good interparticle bonding, thereby maintaining structural integrity against compressive loads [10][14]. In addition, using fly ash in the mixture at a certain proportion can improve the compressive strength, but it can reduce the strength if the proportion of fly ash is too high [15]. This is supported by previous studies where fly ash has the potential to improve compressive strength, but only within certain limits [16]. Other studies also confirm that increasing the proportion of fly ash can reduce compressive strength, especially in mixtures that have a high fly ash content [17]. Therefore, it is important to strike the right balance in material proportions so that they have optimal mechanical properties.

Scanning electron microscopy results of the microstructure of composites consisting of 20 wt% CFA in 80 wt% rLDPE, 30 wt% CFA in 70 wt% rLDPE and 40 wt% CFA in 60 wt% rLDPE show significant differences in material homogeneity and distribution. The composite with 20 wt.% CFA has a more homogeneous microstructure compared to the other two compositions. Good distribution of CFA in the rLDPE matrix ensures strong bonding between materials and improves the mechanical properties of the composite due to optimal cluster formation [10][11].

Efficient load transfer from the rLDPE matrix to the dispersed CFA particles is also a key factor in increasing the mechanical strength of the composite, since increased adhesion between the matrix and filler minimizes the presence of voids and microcracks [12]. A homogeneous and dark-colored rLDPE matrix, as seen in the micrograph, indicates an even load distribution. Localized stress around cavities or filler particles can lead to crack formation, but good CFA distribution can reduce the likelihood of crack propagation [13]. Good distribution of CFA in the polymer matrix promotes the formation of a microstructure that provides high mechanical properties, which in principle improves the overall structural integrity of the composite [15].

The obtained compressive strength of 9.80 MPa in this composite indicates its structural integrity due to the homogeneity of the matrix and strong adhesion between CFA and rLDPE. Previous research shows that low amounts of CFA in rLDPE can increase adhesion between matrix and filler particles, resulting in optimal mechanical strength [10][15]. CFA dispersion not only increases the microstructural density, but also prevents the formation of significant stress concentrations, resulting in efficient load distribution throughout the composite material. In addition, the microstructure reveals the formation of flow patterns that reflect the distribution of materials during the mixing process. Regular flow patterns indicate good mixing, which ensures microstructural homogeneity in

composite materials. A uniform flow pattern is essential to minimize the risk of cracking and mechanical failure [16]. Overall, the combination of even fly ash distribution, few voids and cracks, and a strong and homogeneous LDPE matrix results in excellent mechanical performance for the composite.

Bending strength and elasticity modulus

Table 2 shows a difference in the resulting bending stress value but it is not significant in the proportion of each material. The highest bending stress value of 16 MPa was obtained for a composite 20 wt.% CFA and 80 wt.% rLDPE, with a maximum force of 78.5 N. This result indicates that specimen A distributes the load better before the occurrence of residual deformation compared to samples B and C. Previous research shows that the use of nonwoven fibers in composites can improve the material's performance in bearing bending loads, indicating that the use of an appropriate matrix can increase the bending strength of composites [18].

However, in specimen B (30 wt.% CFA and 70 wt.% rLDPE), a decrease in the maximum force obtained was observed compared to sample A. The maximum force was 78.32 N with a bending value of 15.98 MPa. This decrease in maximum force can be explained by an increase in the proportion of CFA, which can reduce material flexibility and increase stiffness, thereby affecting the material's ability to withstand loads before damage occurs. This is consistent with the results of other studies which show that increasing the filler content can decrease flexibility and increase stiffness, thereby reducing the ability of the composite material to withstand bending loads [19].

The results for sample C with higher CFA content show that increasing CFA content does not always have a positive effect on the flexural strength of the material. Other studies also show that increasing filler content can result in a decrease in the bending strength of composites, especially if the filler is not uniformly distributed in the matrix [20].

Figures 2, 3 and 4 show that there is quite a significant difference in the bending elastic modulus for 20 wt.% CFA in 80 wt.% rLDPE, 30 wt.% CFA in 70 wt.% rLDPE, and 40 wt.% CFA in 60 wt.% rLDPE composites in the elastic, plastic and failure zones. At the initial stage, all three materials demonstrate a nearly linear dependence of stress on deformation, which indicates that in the elastic zone they obey Hooke's law. This shows that material A has greater stiffness, indicating that increasing the stiffness of composite materials can be achieved by changing the material composition.

After the elastic phase, all three curves begin to bend, indicating a transition to the plastic zone before reaching the maximum stress. Material A reaches a maximum bending stress of about 80 MPa, indicating high resistance to bending loads before failure [21].

Composite materials can provide different plastic behavior depending on the composition and structure of the material. The proper composition can influence not only strength but also resistance to deformation. After reaching the maximum point, both curves show a decrease in stress which results in material failure. Material A experiences a more abrupt fall, exhibiting more brittle properties, whereas material C tends to fail suddenly without significant additional deformation. In contrast, materials B and C experience a more gradual decrease in stress, showing more ductile properties [22].

Thus, the addition of filler in composites affects the mechanical properties and resistance to deformation. In this case, materials B and C, with a higher proportion of CFA, show the ability to better absorb energy before failure, which can be an advantage in applications that require resistance to dynamic loads. In the context of structural applications or as composite materials, when choosing between these three materials, it is necessary to consider the balance between strength and impact toughness according to the needs of their use [23].

Table 2: Bending strength test results

Sample Types	Weight of CFA (%)	Weight of rLDPE (%)	Max. Force (N)	σ (MPa)
A	20 wt	80 wt	78.5	16
B	30 wt	70 wt	78.32	15.98
C	40 wt	60 wt	77	15.8

Selection of appropriate materials based on desired mechanical properties is critical for engineering applications. The ductile properties of B and C materials make them more resistant to deformation before failure, which can be an advantage in applications requiring resistance to dynamic loads [24]. Furthermore, strengthening with nanosilica can increase the material's resistance to deformation, which is relevant to this analysis because it shows that material composition can significantly influence the mechanical behavior [25].

4. Conclusion

Research results show differences in strength depending on the proportion of materials. Specimen A (20 wt.% CFA and 80wt% rLDPE) has the highest compressive strength, namely 9.60 MPa, while specimen C (40 wt.% CFA in 60% rLDPE) has the lowest compressive strength, namely 8.67 MPa. Increasing CFA affects the resulting mechanical properties. The bending strength test results show that specimen A also has the highest bending strength, namely 16 MPa, while specimens B and C show a decrease. SEM analysis shows that good distribution of CFA in rLDPE improves the performance of the composite. The optimal composition of 20% CFA and 80% rLDPE provides higher compressive strength.

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