JMSAE Journal of Materials Science and Applied Energy

I. Kasibe et al. / J. Mater. Sci. Appl. Energy. 14(1) (2025) 252394

Comparison of Mechanical Properties of Biogas Packaging Materials

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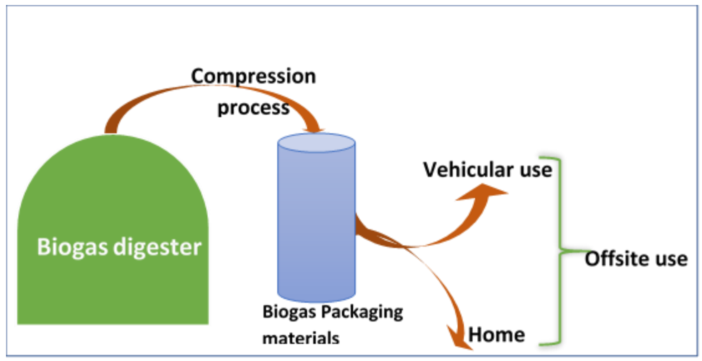
https://doi.org/10.55674/jmsae.v14i1.252394

Received: 16 April 2023 | **Revised:** 12 October 2023 | **Accepted:** 28 December 2024 | **Available online:** 01 January 2025

Abstract

Initiatives of providing biogas onsite are futile without provision for offsite use. This study aims to compare the mechanical strength of materials for packaging biogas. To address the research problem, four materials were considered for the study, including: low-carbon steel, Aluminium, High-Density Polyethylene (HDPE) and fiberglass polyester composite. An experiment was carried out on each of the materials to find out the yield strength and ultimate tensile strength. Results indicate that, whereas steel ranks highest in many strength parameters, including; tensile strength, yield strength, factor of safety, and stress carrying capacity; fiberglass polyester composite closely follows in all measures, and has the highest value of specific strength of all the study materials; with over 58% more weight saving as compared to steel. This property explains the strength-to-weight ratio of a material; which is a key consideration for designing light and strong pressurized gas containers.



Keywords: Biogas; Factor of safety; Packaging materials; Specific strength

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Introduction

Biogas as a versatile energy carrier finds application at household, commercial and industrial levels of a country [1]; with a noticed growing need emerging from rapid population growth, diversified use of the energy, coupled with the gradual shift from fossil fuels to renewable energy [2, 21]. Biogas use in many countries is predominantly on-site, which limits extensive use of the gas in areas far from the production unit. As such, countries like Germany (with over 62% of the European biogas plants), Italy, China, and India [3] have embraced the transportation of biogas by either gas network [4] or packaging in portable containers.

Biogas packaging is hinged on the use of the gas, the packaging material of the gas container and then the quantity and quality of the gas in the container. In effect, studies have highlighted different packaging materials for gas, namely; steel, plastics, Aluminium, and composite materials [5]. Moreover, for whichever material option taken; cost, safety (mechanical strength of container) and capacity are determinants in the packaging consideration [6]. Available literature however, presents steel as a conventional packaging material for gas because of its durability, high mechanical strength and small space occupied as compared to the other packaging materials [7]; even when it's non-corrosion resistant. Worth noting, literature on biogas packaging in containers is scanty, with a limited mention of steel materials in the design of biogas holders, and biogas gas networks. This is however not conclusive owing to the difference in operating pressures in a gas holder, gas grid networks and pressurized gas containers. The pressure in the gas networks can be as low as 2.50 bars, while for biogas in the container, it should be above 47.50 bars (critical pressure). In this paper, selection of the packaging materials is made with great consideration for gases of close similar properties like natural gas, and references for pipe materials used in biogas networks (carrying pressurized gases) [19, 20]. Further consideration was made on the bases of high stress resistance capacity, weight saving, material availability, relatively low cost on the market, recyclability, and corrosion resistance [5, 17, 25, 26]. Domestic Liquefied Petroleum Gas (LPG) cylinders are commonly in use for bottling gas, and according to the ISO standards (for example BS 5045, ISO 11114 – 1, ISO 10286(2), EN ISO 9809 – 2); their pressure level is greater than 14 bars while filling the gas [22]. The properties of yield strength and tensile strength are determined using a tensile test, and are key determinants of the safety of the material carrying pressurized gas. Importantly, the tensile test serves the purpose of enabling material selection for particular application and predicting how a material will perform under normal and extreme conditions [23, 24].

This study aims at exploring suitable materials for packaging biogas, with consideration of their specific strength (which is a function of the ultimate tensile strength of the material), and their factor of safety (load carrying capacity); for a light, safe, strong, and more convenient packaging material for the container.

Materials and Methods

The object of study was the mechanical strength of materials for packaging biogas with a purity of about 98%. With reference to literature on packaging materials for compressed gases like Liquefied Petroleum Gas (LPG), oxygen, natural gas; four packaging materials were selected and studied, namely; low carbon steel, aluminium, High Density Polyethylene plastics, and fiber glass polyester composite. These materials were selected on the bases of high stress resistance capacity, weight saving, material availability, low cost on the market, recyclability, and corrosion resistance (especially fiber glass polyester composite). Importantly, the materials were obtained from respective industries in Kampala, Uganda, for example; Luuka Plastics for HDPE, steel rolling mills for Steel and aluminium, and fiber glass polyester composite from Fiber glass factory in industrial area, Namugongo.

Determination of the Tensile Strength of Materials

The four samples of four different thicknesses for each of the materials were coded according to the type of material and the differentiating thickness. The codes are summarized as below: Aluminium (A), steel (S), HDPE (H) and Fiber glass (G), followed by a number representing the magnitude of thickness of the specimen. The thickness of the respective samples, for example; A2.5, S2.5, H2.5 and G2.5, were expected to be uniform but that could not be attained because the materials were gathered from already manufactured products that come with particular gauges; nevertheless, they were respectively measured on YG141 digital thickness gauge. An experiment based on standards D638M-96 (for plastic), D3039 (fiber glass composite), and ISO 6892 – 1: 2016 (for steel and aluminium) was conducted to determine the mechanical strength of the sample materials of aluminium, steel, fiber glass polyester composite and HDPE plastics on M500 – 25AT Tensile Tester. The major outputs for this study were yield strength and the ultimate tensile strength, since they are determinants of mechanical strength for both ductile and brittle materials. The yield strength is determined by estimating the stress corresponding to the yield point. In the estimation, the offset yield point is taken as the stress at which 0.20% plastic deformation occurs. The ultimate tensile strength is the stress at peak from the experimental values, and comparison is made in relation to the highest and the lowest value samples. The value of tensile strength was used to determine the specific strength of the material from the formula;

$$Specific\ strength = \frac{Tensile\ strength}{density\ of\ material} \tag{1}$$

The combination of tensile strength and yield strength allowed the determination of the factor of safety for each of the specimen using the formula.

$$Factor\ of\ safety = \frac{yield\ strength\ or\ tensile\ strength}{working\ pressure} \tag{2}$$

Fig. 1 Measurement of thickness using YG141 digital thickness gauge at a laboratory in the Faculty of Engineering – Busitema University.

The working pressures in this study were 50 bar and 250 bar, but the latter was considered to provide a better material with a high strength integrity. Additionally, the formula above depends on the nature of material, that is; ductile materials use yield strength while brittle materials like fiber glass use the ultimate tensile strength. These values were compared with steel since it's a conventional packaging material for liquefied gas according to standard BS 5045.

Fig. 2 Materials on the M500 – 25AT Testile tester machine at a laboratory in the Faculty of Engineering-Busitema University.

Results and Discussions

The following plots below from Fig. 3 – 6 were generated from the M500 – 25AT Tensile tester machine report; each describing the relationship of stress against strain for every sample. Out of these plots, the values of yield strength and ultimate tensile strength (respectively Table 1 and Fig. 7) are generated. Fig. 6, indicates that the material does not stretch beyond the yield point before it breaks. As such, for such material; the yield strength and ultimate tensile strength fiber glass polyester composite are the same. This makes the design strength for this material, and so is the internal pressure of the gas. Of all materials, steel has the highest stretch beyond the elastic limit, as evidenced in Fig.4 and Fig. 7. This implies that it can contain more gas for the same volume of the container, without fracturing or deforming; which is unlikely for HDPE. Steel has a record of the highest value of yield strength, averagely 242.25 MPa, followed by fiber glass. HDPE has the least value of yield strength, with an average of 13.06 MPa. In consideration of the highest value of yield strength per material, fiber glass is 23% higher than aluminium and 53% lower than steel (see Table 1, and Fig. 3 – 6 below.

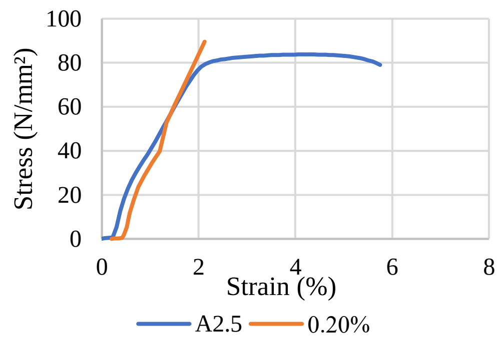

Fig. 3 Stress against strain for aluminium A 2.5.

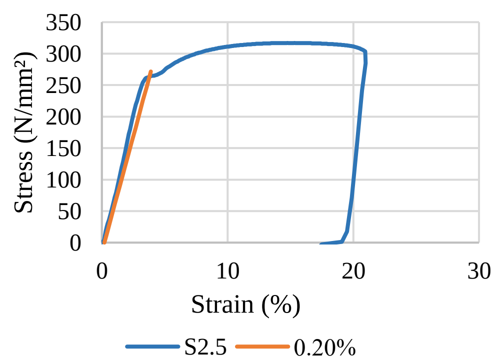

Fig. 3 Stress against strain for steel S2.5.

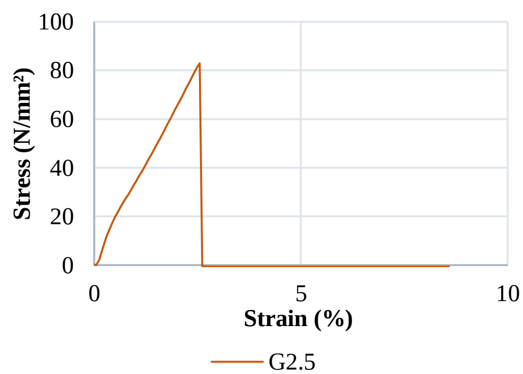

Fig. 4 Stress against strain for fiber glass polyester composite G2.5.

Table 1. 0.20% offset yield strength of the sample materials.

Material Sample	Yield strength (MPa)	Thickness (mm)
A2.5	60.40	3.48
A2.0	30.70	3.04
A1.5	43.90	2.35
A1.2	85.60	1.93
S2.5	272.00	2.86
S2.0	247.00	2.22
S1.5	258.00	1.81
S1.2	192.00	1.42
H2.5	9.38	3.23
H2.0	9.44	2.40
H1.5	23.50	2.11
H1.2	9.92	1.53
G2.5	82.91	3.80
G2.0	90.43	2.25
G1.5	127.73	1.89
G1.2	89.32	1.53

Ultimate Tensile Strength

Tensile strength is the resistance of a material to breaking under tension. Fig. 7 below shows the tensile strength of the sample specimen, with steel recording the highest tensile strength.

Samples of HDPE have the lowest value of tensile strength, and therefore can resist a maximum of 16.6 MPa before it breaks. It's interesting that fiber glass has a higher tensile strength as compared to Aluminium at relatively the same thickness.

Table 2 Specific strength and factor of safety of the study materials.

Materials	Steel	Aluminium	Fiber glass	HDPE
Tensile stress (MPa)	269.30	77.90	97.60	16.60
Yield strength (MPa)	242.25	55.15	97.60	13.06
Density (kgm^{-3})	7850	2770	1200	958
Factor of safety	9.69	2.21	3.90	0.52
Specific strength ($Pa\ m^3kg^{-1}$)	34306	28123	81333	17328

From Table 2, fiber glass had the highest specific strength, translating into 58%, 65%, and 79% higher than steel, aluminium and HDPE respectively. Importantly, steel had the highest value of factor of safety; translating into 60%, 77%, and 95%, higher than fiber glass polyester composite, aluminium, and HDPE respectively. From the table above, HDPE has the least load carrying capacity below the required range for pressure vessels.

Fiber glass polyester composite has the highest specific strength translating into 58% as compared to steel (the conventional packaging material for gas). Whereas in the comparison of the mechanical strength of packaging materials are many properties that can be explored, this study focused mostly on the tensile strength and yield strength of the materials because they directly spell out failure conditions of a pressurized container. Results

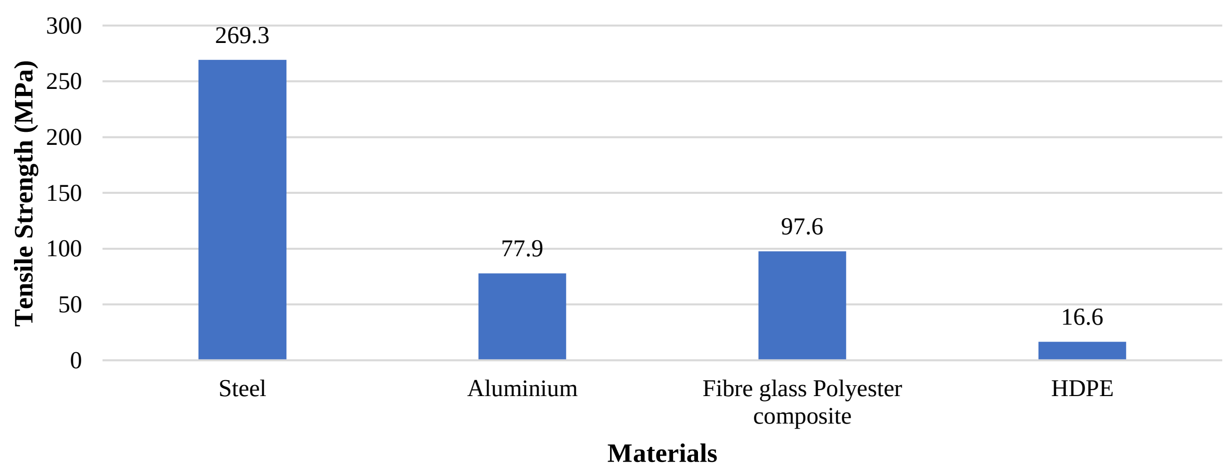

Fig. 7 Stress at peak for the sample materials.

indicate that, of all the study materials, steel has the highest values of the mechanical properties under study. For instance, in consideration of the highest value of yield strength per material, fiber glass is 23% higher than aluminium and 53% lower than steel. Additionally, in consideration of the highest value of tensile strength; fiber glass polyester composite, aluminium and HDPE are respectively 60%, 72%, and 93% lower than steel. This places steel in the best mechanical strength position because of the highest resistance to fracture and deformation. This is followed by fiber glass polyester composite, aluminium and lastly HDPE. The above result is in agreement with many studies, pointing out steel as the strongest material for gas packaging [8 – 10]. Additionally, at a working pressure of 250 bars; steel has the highest average value of factor of safety, with about 60%, 77% and 93% higher safety as compared to fiber glass, aluminium, and HDPE respectively. From literature, however, the factor of safety for pressure vessels in which gas cylinders are included, ranges from 2.50 to 7 [11, 12]. This implies that, fiber glass polyester composite, and steel, are the safest materials for packaging biogas at 250 bars of internal pressure. Additionally, in the design of efficient, convenient, and safe gas containers, specific strength of the material is a key parameter. This allows the determination of the strength to weight ratio, and hence, the weight saving capacity of a material. Whereas steel has the highest strength of all the study materials as discussed above, its specific strength is next to fiber glass polyester composite. The weight saving capacity for fiber glass composite as determined in the results, translates into 58%, 65%, and 79% higher than steel, aluminium, and HDPE respectively; which is in agreement with Tripathi et al. [13], whose weight saving of the fiber glass composite in comparison with steel, is 54.50%. This is partly due to the relatively lower density for fiber glass polyester composite as compared to steel and aluminium, and the reinforcement from the fiber glass and matrix making up the composite, which increases the material stiffness, creep and fatigue properties [14]. This however is not true for HDPE, even when its density is the lowest; because of its tensile strength and yield strength, which are lowest of all the study materials. Further still, a higher specific strength for steel as compared to aluminium contradicts the findings of Asif Iqbal & Nuruzzaman [14] and Varshney & Kumar [15]; even when Wang et al. [9] affirms that steel can have its specific strength increased with the lowering of the material density. This is mostly done by forming composite materials with lighter and resilient materials; whose average density is lower. Such materials such as fiber glass composite are lighter, and stronger; which is recommended for gas containers, as confirmed by Tripathi et al. [13], Bandpatte [16], Dhanunjayaraju & Babu [17], and Chalamaiah & Leelasarada [18]; and a suitable replacement or complement of steel as a gas packaging material.

Conclusion

In the comparison of the mechanical strength of the proposed packaging materials for biogas; the safety and weight saving properties of the material making up the container revealed two standout materials, thus; steel and fiber glass polyester composite. On the basis of factor of safety and specific strength, fiber glass polyester composite and steel are the most suitable materials for packaging biogas at a purity above 98%.

The findings in this study present many material options for packaging biogas in portable containers and large tanks (under high internal gas pressures), and even other storage applications and gas grid networks. Steel is a conventional material for packaging pressurized gases but presents some short falls especially under corrosion agents like Hydrogen sulphide for biogas. As such, the identification of other materials with relatively better properties like fiber glass (which is light, strong, safe, corrosive resistant and convenient packaging material for biogas; ranking highest at 58% higher than steel in weight saving); presents more options for safety, and convenience.

Acknowledgements

Importantly, I extend my gratitude to the Faculty of Engineering Busitema University for the assistance given in availing their equipment for my data collection; MAPRONANO for the research grant offered to accomplish the research task, it was timely and helpful, and Makerere University and Bugema University for the mentorship and good research environment.

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