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Sealing performance analysis of composite gaskets made of silicone rubber filled with ramie natural fibers

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ABSTRACT

Silicon rubber gaskets are commonly used in many industries for low pressure sealing conditions only. The research studies about the sealing performance improvement of a novel composite gasket made of the silicone rubber filled with ramie natural fibers in a bolted joint connection. In this research the sample of gasket consists of 4 different types of gasket i.e. a pure silicone rubber gasket and the silicone rubber composite gasket with 1, 2 and 3 layers of ramie fiber woven. The gaskets are tested using a water pressure testing equipment with a variation of internal fluid pressure and difference torques at 8 N.m, 12 N.m, 16 N.m and 20 N.m. The sealing performance is measured based on the maximum fluid pressure that can be hold by the gaskets before the fluid leaking occurred. The results show that the silicone rubber composite gaskets have better sealing performance comparing with the pure silicone rubber gaskets where the silicon rubber gaskets capable to hold the internal fluid pressure until around 5 times rather than pure silicon rubber gaskets (0.17 MPa comparing with 0.90 MPa). On the other hand the sealing performance of the composite gasket with 3 layers is almost 2 times better than the composite gasket with 1 layer and around 1.5 times better than the composite gasket with 2 layer of fiber woven.

Keywords: Silicone rubber; sealing performance; ramie natural fibers; bolted joint.

INTRODUCTION

Seals are very important devices to prevent fluid leaks in a bolted joint connection [1]. Silicone rubbers have been widely used as seal elements or gaskets and play important roles in piping connections in some industries such as food industries, automotive industries, oil and gas industries, etc. However silicone rubbers can be applied in low pressure environments only [2]. Figure 1 shows a general gasket installation in a bolted joint connection.

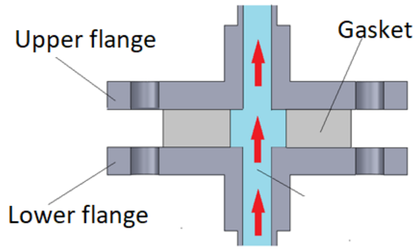


Figure 1. General gasket installation in a bolted joint connection.

Some researchers investigated about the silicone rubber characteristics/ properties and the effects of the fibers in the silicone rubber material properties for many applications [3-13]. Other studies investigated about the sealing performance of the gasket using diferent materials [14-18]. Some researchers used a finite element (FE) simulation method to evaluate the sealing performance of the gasket [15-22] while the other researchers used an experimental work to analyse the sealing performance [1,3,7,14,15]. Noshirwaan et al. [12] review the characteristics and applications of various gasket made of metals, non-metals, polymers and hybrids while Layth et al. [13] provide a comprehensive review of the natural fiber reinforced polymer composites (NFPC) and their applications. Noshirwaan et al. stated that as a gasket application the silicon rubber is a material of choice for moderate strength and elasticity while Layth et al. concluded that chemical treatment of the natural fibers improved the physico-mechanical and thermochemical properties of the NFPCs. Effects of the additional fiber such as palm fiber, or woven fabrics to improve the mechanical properties of composites also conducted by some researchers [23-25], which show that these materials could improve the properties of the composites significantly.

Persson and Yang [1] firstly introduced a theory relates to leak-rate of seals based on the percolation theory and contact mechanics theory. Persson and Yang analysed the role of surface roughness in the interface between a rubber and a hard counter surface at different magnifications. Yang et al. [3] investigated the fabric reinforced rubber composites of tubular seals using finite element simulation and experimental work. Yang et al. concluded that the existence of the fabric increases the compression force and improved the sealing performance of the tubular rubber seal. Yin et al. [4] studied about carbon fibers lattice structure filled with silicone rubber and found that this type of composite experienced higher stress level region which is very good in term of energy absorption and good sealing performance. Wen et al. [5] studied characteristics of nano-hydroxyapatite/silicone rubber composite for medical application, while Wang et al. [6] used carbon fiber combined with silicone peroxide as silicone rubber reinforcement. Meunier et al. [7] performed mechanical characterization which consists of tensile, pure shear, compression, plain strain compression and numerical modeling for an unfilled silicone rubber. Lorenz and Persson [14] experimentally investigate the leak rate of rubber seals and compare the results with the percolation theory and contact mechanics theory.

Some researchers focused on the sealing performance of gaskets made from different materials. Choiron et al. [22] evaluated the effects of contact area to sealing performance of the corrugated metal gasket based on FE simulation and helium leak test experiment. It was found that higher contact area and contact stress between flanges and gasket provides better sealing performance of the corrugated metal gasket. Nurhadianto et al. [19-20], Karohika et al. [21] and Choiron et al. [22] investigated the effects of contact area and contact stresses in the sealing performance of the corrugated metal gasket. Choiron et al. [15] used a water pressure test equipment to evaluate the sealing performance of the gasket. Choiron et al. [22] also used a helium leakage equipment to analyse the sealing performance of the metal corrugated gasket.

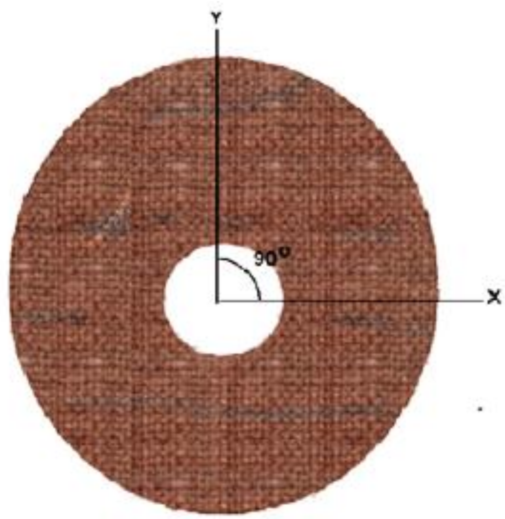
Through a comprehensive literature review shows that there are no scientific studies reported on the silicone rubber composite filled with natural fibers and still there is a gap in the silicone rubber composite filled with natural fibers research field especially for gasket applications. This study will be investigating the sealing performance improvement of the silicone rubber gasket in the bolted joint connection by addition of ramie natural fibers.

METHODS AND MATERIALS

Materials

In this study, the composite gaskets were made of the acetic silicone rubber filled with the ramie (Boehmeria nivea) natural fiber woven and flanges were made of stainless steel SUS304. Figure 2a depicts the ramie natural fiber woven which is used in the research while Figure 2b shows the orientation angle of the ramie fiber woven.

(a)



(b)

Figure 2. (a) Ramie natural fiber wofen and (b) orientation angle of the ramie fiber.

Table 1 shows the ramie fiber properties. The average thickness of the ramie fiber woven is 2.3 mm. Table 2 shows the material properties of SUS304 while Table 3 presents the properties of the acetic silicone used in the research.

Table 1. Material properties of Boehmeria nivea/ramie [11].

Property (unit)	**Value**
Density (g/cm3)	1.5
Tensile strength (MPa)	500
Young’s modulus (GPa)	44
Elongation at break (%)	2

Table 2. Material properties of SUS304 [26].

Property (unit)	**Value**
Tensile Strength, Ultimate (MPa)	505
Tensile Strength, Yield (MPa)	215
Modulus of Elasticity (GPa)	193 - 200
Elongation at break (%)	70%
Poisson's Ratio	0.29
Shear Modulus (GPa)	86

Table 3. Material properties of Acetic Silicone [27].

Property (unit)	**Value**
Specific gravity (ISO 2811-1)(g/ml)	95
Flow resistance (ISO 7390), (mm)	≤ 2
Skin formation time (min)	15
Curing rate (days / 5mm)	2-3
Application temperature (°C)	+ 5 to + 40
Shore A hardness (DIN 53505)	16
Elastic recovery (%)	>80
Temperature Resistance (°C)	- 30 to + 120
Modulus at 100% elongation (N/mm2)	≤ 0,3
Elongation at break (%)	130

The mass of silicone rubber composite gasket filled with ramie fiber, m, can be define as:

$$m = \rho_s v_s + \rho_r v_r \tag{1}$$

where ρ_s and v_s are density and mass of the silicone rubber, while ρ_r and v_r are density and mass of the ramie fiber woven.

Gasket and Flange Geometry

Figure 3 to Figure 5 show the details dimension of the gaskets and flanges as well as the real models that have been produced. The diameter of the gasket is referring to the 50A standard on JIS B 2404.

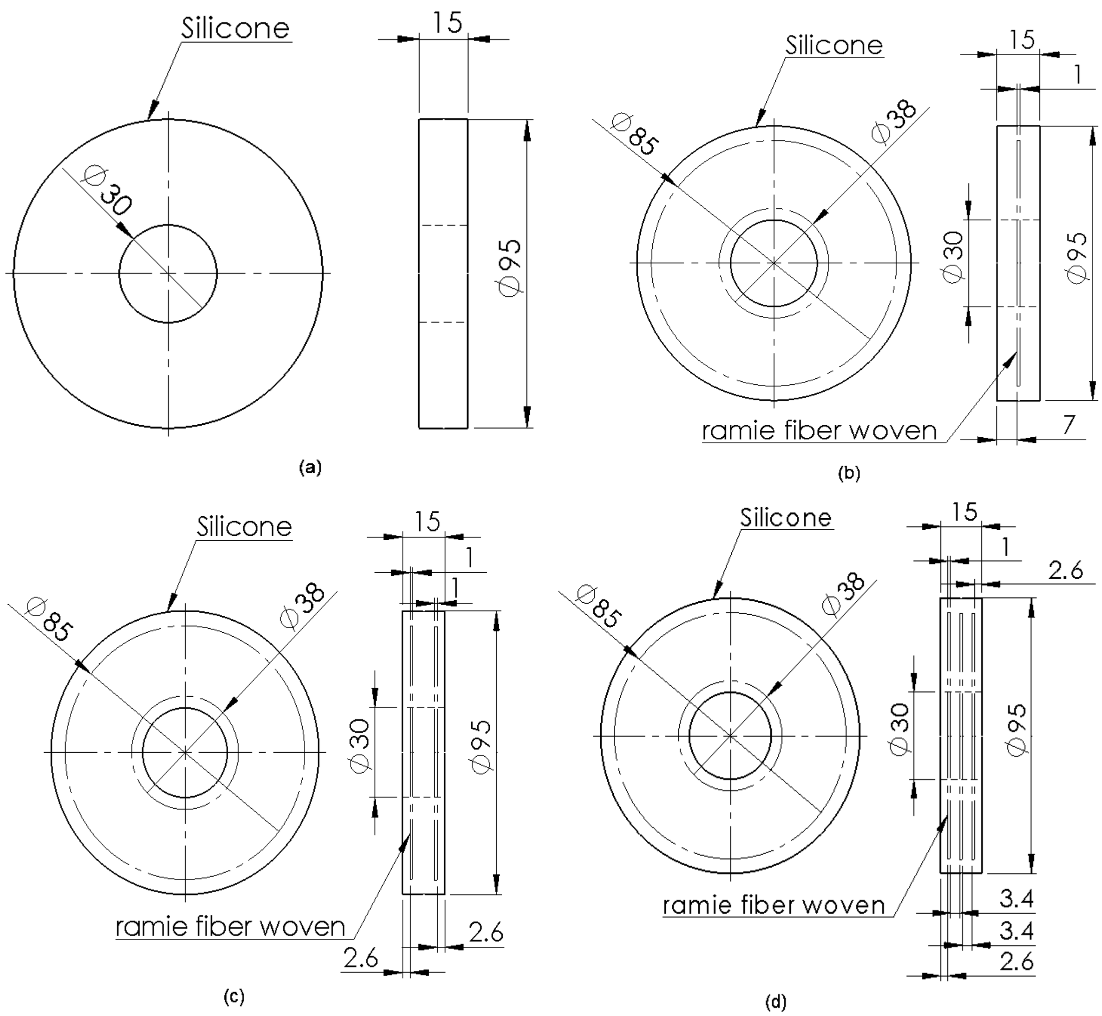


Figure 3. Gaskets dimensions (a) gasket type 1; (b) gasket type 2; (c) gasket type 3 and; (d) gasket type 4.

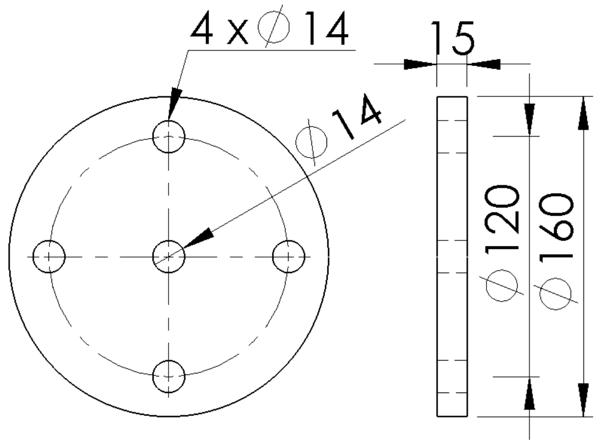


Figure 4. Stainless steel flange dimensions.

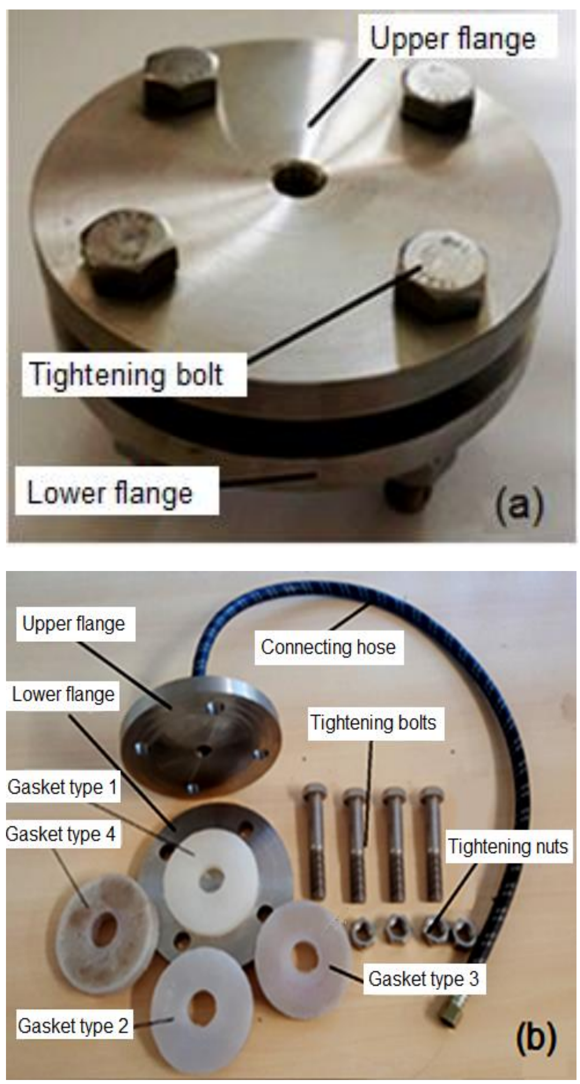
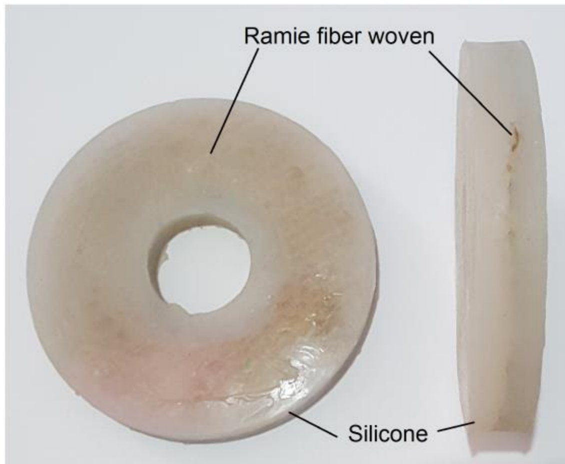


Figure 5. (a) gasket-flanges full assembly and; (b) gasket flanges assembly components.

Gasket Manufacturing

The gaskets were made by a gravity molding process using a simple mold. The curing process occurred in a room temperature and at an atmospheric pressure for around 72 hours to ensure that the internal region of the gasket perfectly cured. Figure 6 shows a sample of the silicone rubber gasket with a single layer of ramie fiber woven.



(a) (b)

Figure 6. A sample of the silicone rubber gasket filled with a single layer of ramie fiber woven (a) top view and; (b) side view.

Before the gasket manufacturing process, the ramie fiber woven laid in the oven at temperature of 80^{o}C for around 10 minutes. This process is required to remove moisture which may deteriorate the gasket properties. The gasket in the research consists of four different types is shown in Table 4.

Table 4. Silicon rubber gasket types.

No	Type of gasket	Average Mass (gram)	
		Silicone	Ramie
1	Pure silicone	100.2	0
2	Silicone with single layer ramie woven	97.1	3.1
3	Silicone with double layer ramie woven	94.1	6.2
4	Silicone with triple layer ramie woven	91.1	9.2

Gasket Compression Test

The gasket samples were tested in the universal testing machine SHIMADZU AGS-20kNX which has maximum capacity of 20 kN as shown in Figure 7. The test was performed to obtain the compressive property of the silicone rubber composite gaskets. The samples were compressed at the displacement rate of 10 mm/min at a room temperature. The maximum vertical displacement of the loading board is 5.5 mm, which is equal to around 36% of the initial gasket thickness.

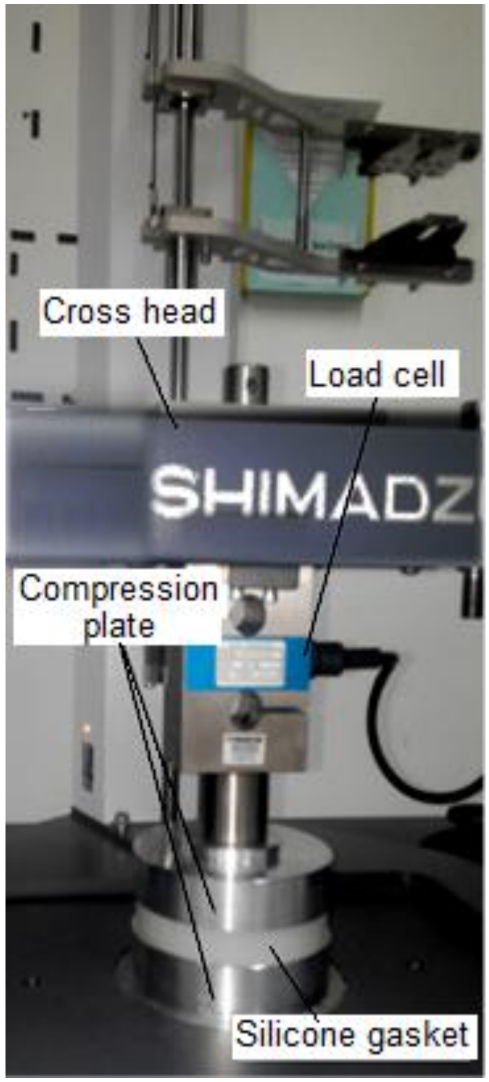


Figure 7. Gasket compression test in the universal testing machine Shimadzu.

Water Pressure Experimental Set-Up

The gasket and flanges were assembled then located in the supporting fixture and the connecting hose is attached securely to the water pressure pump outlet and to the upper flange inlet as shown in Figure 8.

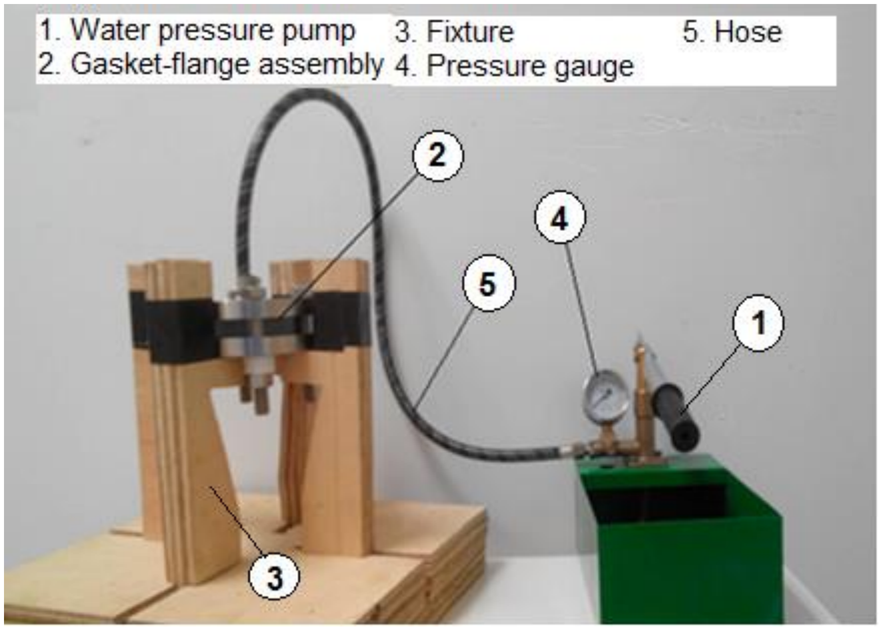


Figure 8. Water pressure leak test installation.

The bolts then tightened using an adjustable torque wrench with initial torque of 8 N.m. After the water leak test for this initial torque, the torque then increased at 12 N.m, 16 N.m and 20 N.m consecutively.

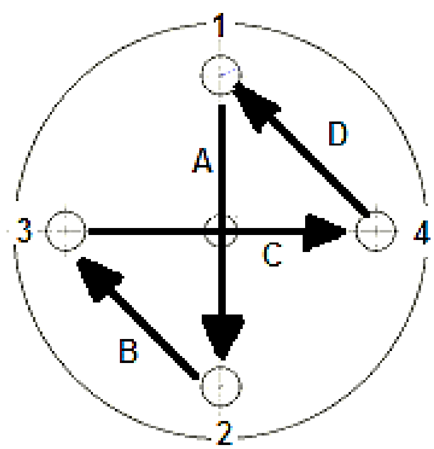


Figure 9. Bolts tightening sequence method.

Figure 9 shows the bolts tightening sequence method to obtain equal torque between every bolt and uniformly distributed stresses on the gasket surface. The tightening process sequence is 1 – 2 – 3 – 4 and this process was performed several times until all of the bolts experienced equal value as defined in the torque wrench.

Water Pressure Test Procedure

In this experiment, the sealing performance of the gaskets is evaluated based only on the evidence of the fluid leaks around the gasket-flange assembly while the leak quantity and leak rates of the fluid are neglected.

The fluid used in the experiment is water and the water pressure pump was used to provide an internal pressure until around 1 MPa. First the gasket was installed in the water pressure test rig then the torque applied at certain value i.e. 8 N.m, 12 N.m, 16 N.m and 20 N.m consecutively. The fluid pressure then applied by pumping the water pump until the fluid leaking detected and the pressure gauge drops rapidly. Every sample of the gasket (3 samples for each type) was observed and the maximum pressure value just before leaking occurred was recorded.

RESULTS AND DISCUSSION

Gasket Compression Test

Figure 10 shows the compressive responses of the pure silicone rubber gasket and silicone rubber composite gaskets filled with ramie fiber obtained from the universal testing machine SHIMADZU. The energy absorption capacity per unit volume, W_v of the gasket can be defined from the total area under the stress-strain curve.

$$W_v = \int \sigma \, \varepsilon \, d\varepsilon \quad (2)$$

For the silicon rubber composite gasket filled with ramie fiber, the energy absorption can be defined as:

$$W_c = \int \sigma_s \varepsilon_s \, d\varepsilon_s + \sigma_r \varepsilon_r \, d\varepsilon_r + \sigma_i \varepsilon_i \, d\varepsilon_i \quad (3)$$

where the subscript c refers to composite gasket, s indicates the silicon rubber, subscript r indicates the ramie natural fibers and i indicates the interface between the ramie and the silicone rubber.

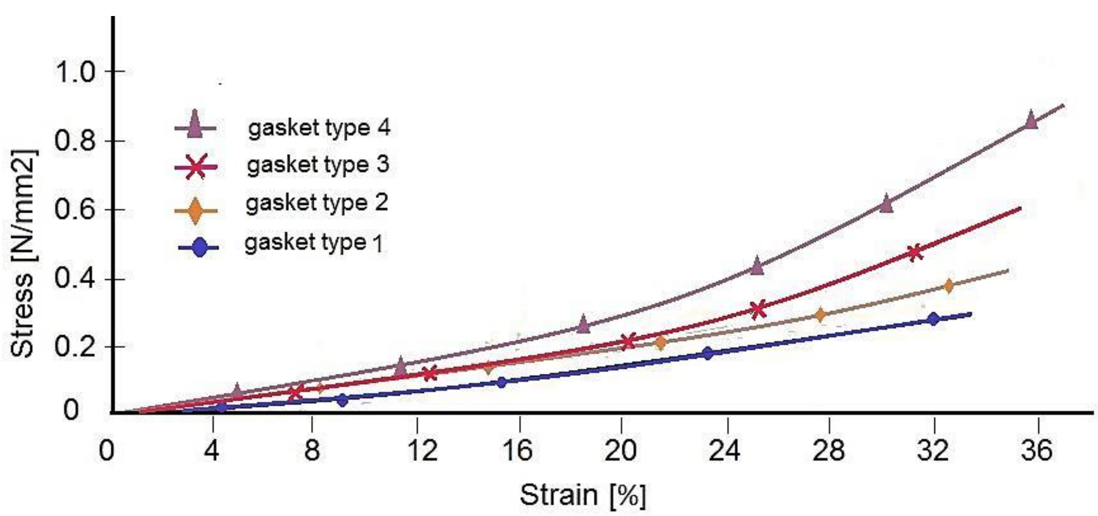


Figure 10. Compression test result for 4 different types of gasket.

It can be seen that the 3 types of gasket filled with fiber woven produce nearly the same curves while the pure silicone gasket produces almost linear curves. The pure silicone gasket (type 1) experienced lowest compressive stress and the gasket filled with 3 layers of woven ramie fiber (type 4) experienced highest compressive stress. Comparing the 3 composite gaskets filled with ramie fiber (type 2, 3 and 4), the stress level of the type 4 around tripled of the stress level of type 2 and the stress level of type 3 almost doubled compared to the type 2. The compressive stress increment from the test relates with the increasing stress at the interface between the silicon and the ramie fiber woven.

It can be seen also that the energy absorption capacity per unit volume of the type 4 (silicone gasket with 3 layers of the ramie fiber woven) gasket has been improved significantly compared to the type 1 (pure silicone gasket) as well as with the type 2 (silicone gasket with 1 layers of the ramie fiber woven) and with the type 3 (silicone gasket with 2 layers of the ramie fiber woven).

From this experiment, it can be concluded that the existence of the ramie woven increases the compressive stress of the silicon rubber composite gasket. This result shows a good agreement with the previous results produced by Yang et.al [3] and Yin et al. [4].

Water Pressure Test Result

Figure 11 to Figure 15 present data obtained from the water pressure leak test. The pressure value presented here shows the condition where leaks occur at a certain torque from 8 N.m to 20 N.m. The data presented are taken from 3 samples/gaskets for each type of gasket.

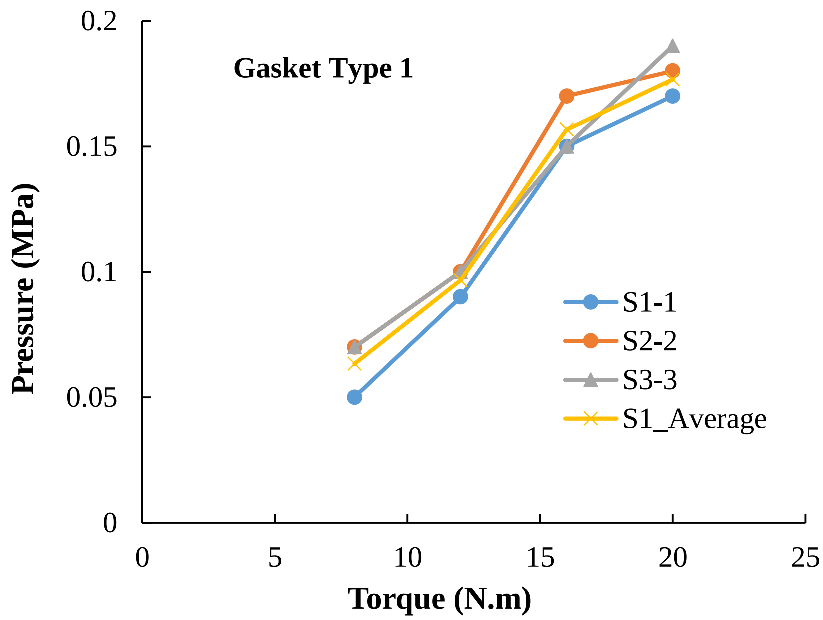


Figure 11. Water pressure test result for the gasket type 1.

Figure 11 shows the experimental result for the gasket type 1 (pure silicone rubber gaskets) for the three samples (S1-1 to S1-3). At the lowest torque (8 N.m) the gaskets experience leaking between 0.05 MPa to 0.07 MPa of the internal fluid pressure with the average value at 0.06 MPa. It can be seen from the graph that the maximum pressure that can be holding by the gaskets increased as the torque increased. For the maximum torque at 20 N.m the gaskets show the better sealing performance result where the maximum pressure before leaking achieved between 0.17 MPa to 0.19 MPa with average value at 0.18 MPa.

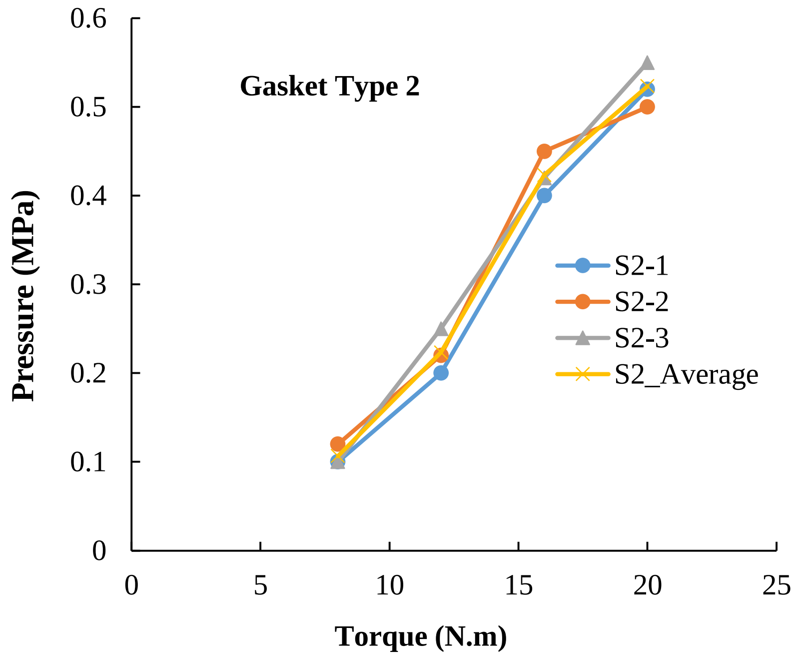


Figure 12. Water pressure test result for the gasket type 2.

Figure 12 depicts the experimental result for the three samples of the gasket type 2 (S2-1 to S2-3). At the lowest torque (8 N.m) the gaskets experience leaking at 0.10 MPa, 0.12 MPa and 0.10 MPa for the sample S2-1, S2-2 and S2-3 respectively, with the average value at 0.11 MPa. At the maximum torque of 20 N.m the gaskets show the higher sealing performance result with the maximum pressure before leaking at around 0.50 MPa to 0.55 MPa with average value at 0.52 MPa. Comparing with the gasket type 1, the sealing performance of the gasket type 2 increased significantly at higher torque.

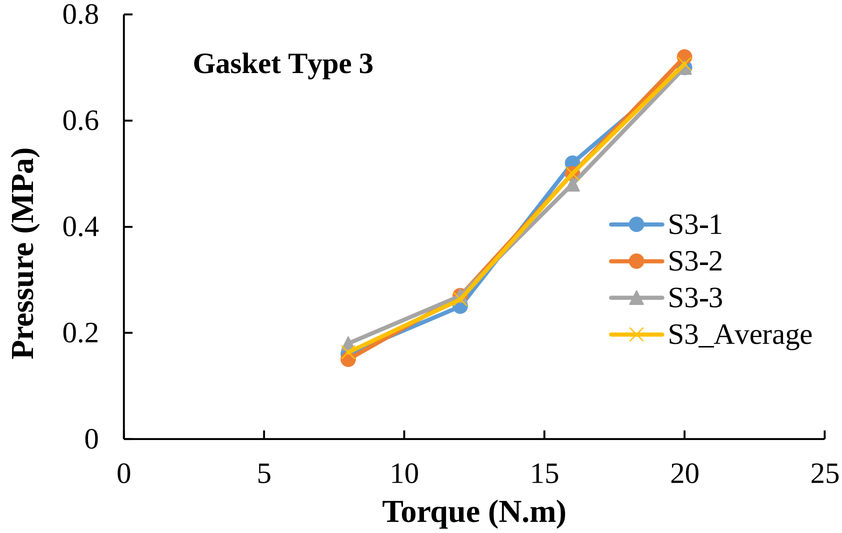


Figure 13. Water pressure test result for the gasket type 3.

Figure 13 illustrates the experimental result for the three samples of the gasket type 3 (silicone rubber composite gaskets with 2 layers of ramie woven) for the (S3-1 to S3-3). At the lowest torque (8 N.m) the gaskets experience leaking at 0.16 MPa, 0.15 MPa and 0.18 MPa for the sample S3-1, S3-2 and S3-3 respectively, with the average value at 0.16 MPa. At the maximum torque of 20 N.m the gaskets show the better sealing performance result with the maximum pressure before leaking achieved the average value at 0.71 MPa. Comparing with the gasket type 2, the sealing performance of the gasket type 3 increased at around 0.2 MPa especially at the torque of 20 N.m.

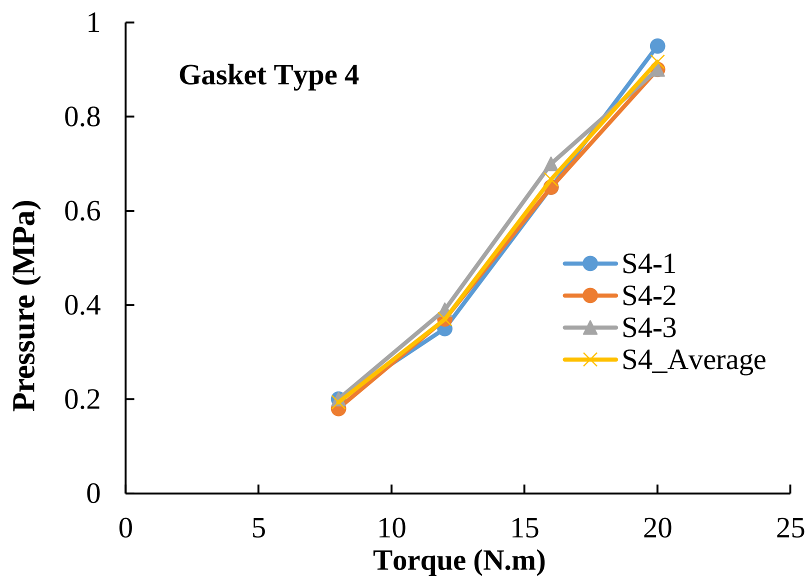


Figure 14. Water pressure test result for the gasket type 4.

Figure 14 explains the experimental result for the gasket type 4 (silicone rubber composite gaskets with 3 layers of ramie woven) for the three samples (S4-1 to S4-3). At the torque (8 N.m) the gaskets experience leaking between 0.18 MPa to 0.20 MPa of the internal fluid pressure with the average value at 0.19 MPa. For the maximum torque at 20 N.m the gaskets show the best sealing performance result where the maximum pressure before fluid leaking achieved the highest value at the average of 0.92 MPa.

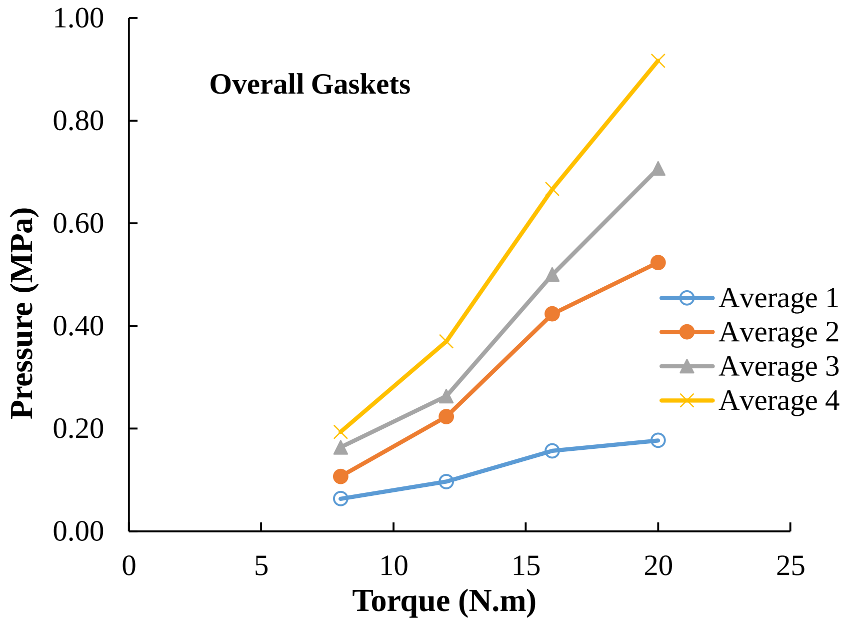


Figure 15. Water pressure test result for all gaskets.

Figure 15 explains the experimental result for the overall gaskets (gasket type 1 to gasket type 4). The results show that in the gasket type 1, which is a pure silicone gasket (without ramie fiber woven), the leak occurred at the lowest fluid pressure around 0.06 MPa with the torque at 8 N.m while the gasket type 4 indicates the highest fluid pressure at around 0.20 MPa at the same torque. When the torque increased the leak occurred at higher fluid pressure with the maximum pressure of 0.17 MPa at 20 N.m of the torque for the gasket type 1 and 0.90 MPa for the gasket type 4.

In the gasket application, the bolts provide torsions which then converted as tightening forces resulting contact stresses between contact surfaces (i.e. between the lower flange surface and the lower surface of the gasket and between the upper flange surface with the upper surface of the gasket). It can be understood that as the torque increases the contact stress between the gasket and flanges also increases. It can be concluded also that the sealing performance of the gasket increases as the torque increases. These results agree with the results from previous researchers [4, 14-15, 19-22] which stated that the sealing performance of the gasket increases as the contact stresses increase.

It can also be seen clearly that the sealing performance of the gasket increases with the number of the ramie woven layer. Comparing the pure silicone gasket (the gasket type 1) and the composite gasket with 3 layers of ramie woven, the maximum fluid pressure that can be hold is around 3 times at torque of 8 N.m and more than 5 times at the maximum torque (20 N.m).

Observing the sealing performance of the silicone gasket filled with ramie fiber woven only (type 2, 3 and 4), it can be seen that the leaks occurred at a higher value of the internal fluid pressure comparing with the pure silicone gasket. Focusing only to the silicone gaskets filled with the ramie woven, the leak occurred at 0.1 MPa on the gaskets type 2 and increased almost 1.5 times in the gaskets type 3 and more 2 folds in the gaskets type 4. In the highest torque value, the leak of the gasket with the ramie woven occurred at fluid pressure of 0.52 MPa on the gaskets type 2 and in the gaskets type 4 the leak occurs at a fluid pressure of 0.95 MPa, which is almost 2 times of the gaskets type 2. It can be concluded that the ramie fiber woven improved the sealing performance of the silicon rubber composite gasket.

CONCLUSION

In this paper, we discuss the sealing performance of a novel silicone rubber composite gasket made of the acetic silicone rubber filled with the ramie fiber woven. The 4 samples of gaskets (pure silicone rubber gaskets, silicone rubber gaskets with 1, 2 and 3 layers of the ramie fiber woven) have been produced and tested. The initial compression tests for the gaskets showed that the stress level increased as the number of the ramie woven layer increased. Comparing with the pure silicone rubber gaskets, the silicone rubber filled with the ramie fiber gaskets indicate a significant increment which is almost 5 times on the gasket type 4 (silicone rubber composite gaskets with 3 layers of ramie fiber woven). The sealing performances of the gaskets also show similar responses. The pure silicon rubber gaskets only capable to hold the maximum pressure at 0.2 MPa while the silicon rubber composite gaskets until 0.9 MPa at 20 N.m of torque which is almost 5 times comparing with the pure silicone rubber gasket. The results show that the sealing performance of the silicone gasket can be improved by increasing the ramie woven layer.

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