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An Experimental Study on Investigation of Carbon Fiber- Silicone Interfacial Shear Strength

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Abstract: The aim of this study was to investigate how interface shear strength of silicone and carbon fiber tow changes by mixing three different types of additives into silicone. As the interest on polymer matrix composites has been rising in last decades in a certain manner in many fields like defense, aerospace and sports, understanding and improving the characteristics of these materials arouses interest. This work focused on the behavior of silicone matrix. As the silicone's viscosity is higher than many other resins, it's wetting ability is not enough to penetrate through the tows of reinforcing fabrics. Various additives can be utilized to decrease the viscosity whereas the effects of these additives on the fiber-matrix interface shear strength are not well-known. Fiber pull-out testing was designed to see how the apparent interfacial shear strength changes via changing the additive.

Keywords: Silicone, carbon fiber, interfacial shear strength, fiber pull-out test.

Karbon Fiber-Silikon Arayüzey Kayma Kuvvetinin İrdelenmesi Üzerine Deneysel Bir Çalışma

Özet: Bu çalışmanın amacı, üç farklı katkı maddesinin silikona karıştırılarak silikon ve karbon fiber demetinin arayüzey kayma mukavemetinin nasıl değiştirdiğinin araştırılmasıdır. Son yıllarda polimer matrisli kompozitlerin kullanımı savunma, havacılık, spor gibi alanlarda belirli bir şekilde arttığından, bu malzemelerin özelliklerini anlamak ve geliştirmek ilgi çeker hale gelmiştir. Bu çalışma silikon matrisin davranışına odaklanmıştır. Silikonun viskozitesi diğer birçok reçineden daha yüksek olduğu için, ıslatma yeteneği, takviye edici kumaşların fiberlerinin arasına sızmak için yeterli değildir. Viskoziteyi düşürmek için çeşitli katkı maddeleri kullanılabilirken, bu katkı maddelerinin fiber-matris ara yüzeyinin kayma mukavemeti üzerindeki etkileri iyi bilinmemektedir. Fiber çekme testi, katkı maddesinin değiştirilmesiyle görünür ara yüzey kayma mukavemetinin nasıl değiştiğini görmek için tasarlanmıştır.

Anahtar kelimeler: Silikon, karbon fiber, arayüzey kayma mukavemeti, fiber çekme testi.

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1. Introduction

Subject of this study is experimental investigation of the mechanical properties silicone matrix composites utilized in aerospace industry. Most of the composite materials used today are produced with epoxy, polyester and vinyl ester based resins and such resins have a rigid structure. Parallel to the development of technology, especially after 2000, scientists are studying the design and use of composite structures with elastic matrix in aerospace applications. The resin type utilized in the manufacturing of these composite structure is a silicone based material which has a soft structure. The main difference between these two types of resins is; rigid resin shows liner behavior under load, while soft (elastic) resin exhibits non-liner behavior. Unlike traditional matrix materials, these materials have very low bending stiffness, allow bending and multiple foldings, not showing any damage. The reason for this is the ability of the fibers to move within the silicone matrix [1-4].

Two important features of these structures are highlighted and their applicability to two different industries is explored. One of these features is the foldability of silicone matrix composites a low stress values without damage [5-9]. With this feature, space structures such as solar sails and reflector antenna with large surface area can be folded in a compact manner and sent to the space. The second important feature is that the silicone matrix allows elongation of the composite to be increased up to 100-200%. With this feature, wing profiles or sizes can be changed according to weather conditions [10-13].

In the preliminary work, it has been found that the viscosity of the silicon is too high to wet the carbon fiber yarns it must be reduced. In this study, what particularly worked on is how the carbon fiber-silicone interfacial shear strength changes with mixing of the other low viscosity additives.

2. Experimental

The target in this study was to examine the effects of different additives on silicone-carbon fiber interface shear strength. Three different types of additives were used; silicone oil, thinner and dichloromethane. Row carbon fiber-silicone samples were also prepared to compare with other samples.

2.1. *Sample Preparation*

Silicone resin was selected as it will be used as matrix material in future works. Water bottle lids were utilized to fill and cure silicone in them. A fiber tow was inserted into each lid and allowed to touch on base perpendicularly as shown in Fig. 1. The lids were filled with silicone to a certain level than left to cure at room temperature.

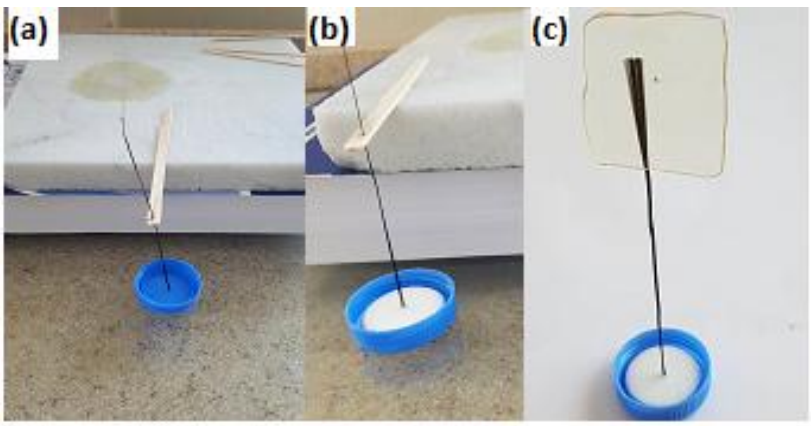

Figure 1. Presentation of sample preparation.

An easy to reach RTV-2 mold silicone was employed in this study. Supplier indicated to mix 3-4% w.t. hardener, whereas it was seen that the silicone cured very fast as 30-60 seconds when mixing in specified ratio. 1% weight was tried and curing speed was satisfying. An 11 mm fiber tow inserted into the lid and fixed perpendicularly as can be seen in Fig. 1a. After that, silicone mixed with hardener and poured into the lid until a certain level. All lids tried to be filled to the same level to guarantee embedded length of carbon fiber to be approximate for each sample. Silicones left for total curing for one day at room temperature. As the fiber tow is not enough thick to grip between tensile testing jaws, other end of the fiber was embedded in epoxy and left epoxy for curing for one day. An example of final sample is shown in Fig. 1c. Four groups of samples were prepared and four samples prepared for each group. First group was silicone without any additives and other mixed with silicone oil, thinner and dichloromethane by 30 % w.t. After mixing with additives, hardener mixed 1% weight of only silicone. Name and specifications of each sample is illustrated in Table 1.

Table 1. Name of specimen groups and additives.

Specimen Name	**Additive (30% w.t.)**
RTV2-Y	none
RTV2-S	silicone oil
RTV2-T	thinner
RTV2-D	dichloromethane

2.2. Testing

Interface shear strength of silicone and carbon fiber was carried out with universal testing machine Shimadzu AG-IS 100 kN. As the jaws are not suitable to grip lid, a steel apparatus shown in Fig. 2a was designed and prepared. It holds the specimens as displayed in Fig. 2b. After holding specimens, they were loaded at speed rate of 0.01 mm/min. Maximum interface shear force obtained for each specimen. Following the fiber separation from silicone, silicone was cut from middle section to measure embedded length l_e of fibers. Length of embedded fiber surface d_f was measure to calculate maximum carbon fiber-silicone apparent interface shear strength τ_{app}.

Fiber ends were cut and examined with optical microscope to search for residual silicone amount after separation of fiber from silicone matrix.

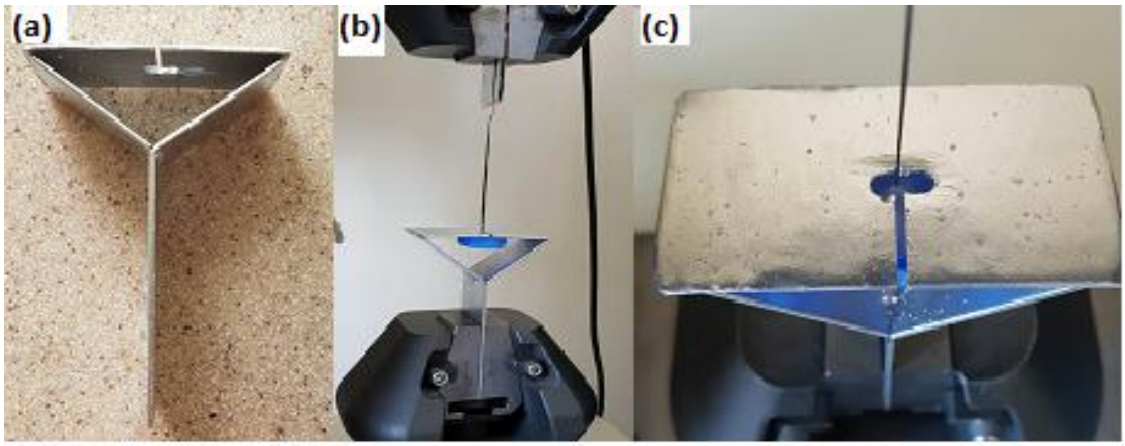

Figure 2. a) Apparatus prepared to hold specimen from base. b) Illustration of specimen holding. c) Image captured during loading process.

3. Results and Discussion

Maximum interface shear force F_{max} was obtained through fiber pull-out test and τ_{app} was calculated for each specimen and Formula 1 was implemented [14];

$$\tau_{app} = \frac{F_{max}}{\pi d_f l_e} \quad (1)$$

Formula 1 was designed for fibers with circular cross-section but samples were prepared with fiber tows in this study and they nearly has rectangle cross-section. Because of this reason πd was changed to circumference of rectangle cross-section. Table 2 illustrates dimensions, F_{max} and τ_{app} of each specimen and mean value of groups.

According to results, addition of dichloromethane enhanced the interface strength 6% comparing to neat silicone whereas, silicone oil and thinner dropped 12% and 15% respectively. The reason for these results can be the decreasing viscosity increased wetting capability. As the wetting capability increased, more silicone resin dispersed on carbon fiber surface and more contact area between carbon fiber and silicone provided.

Examining the images in Fig. 3, it can be seen that fiber pulled from RTV2-D specimens has more residual silicones than other groups. Considering they succeeded the higher τ_{app}, it can be said that dichloromethane addition in silicone matrix enhances interface strength and wetting capability.
Fiber embedded into neat silicone does not have observable residual silicone whereas thinner added silicone specimens showed poorer τ_{app} than others.

Table 2. Apparent shear strength of each specimens.

Specimen Name	embedded fiber length Le (mm)	length of adherent fiber surface ,df (mm)	Fmax (mN)	Interface Shear Strength (x 10^{-3} MPa)
RTV2-Y1	3.55	3.4	53125	4401.408451
RTV2-Y2	3.48	3.4	46875	3961.713996
RTV2-Y3	4.44	3.4	37500	2484.101749
RTV2-Y4	2.76	3.4	56250	5994.245524
MEAN Y1-4	3.5575	3.4	48437.5	4004.588483
RTV2-S1	4.02	3.4	46875	3429.543459
RTV2-S2	4.385	3.4	53125	3563.283922
RTV2-S3	4.95	3.4	59375	3527.926322
RTV2-S4	4.41	3.4	53125	3543.0839
MEAN S1-4	4.44125	3.4	53125	3518.153673
RTV2-T1	3.27	3.4	34375	3091.833064
RTV2-T2	3.82	3.4	53125	4090.314136
RTV2-T3	4.18	3.4	40625	2858.499859
RTV2-T4	3.27	3.4	40625	3653.98453
MEAN T1-4	3.635	3.4	42187.5	3413.504329
RTV2-D1	3.99	3.4	53125	3916.0401
RTV2-D2	3.75	3.4	62500	4901.960784
RTV2-D3	3.75	3.4	50000	3921.568627
RTV2-D4	4.09	3.4	59375	4269.739681
MEAN D1-4	3.895	3.4	56250	4247.526995

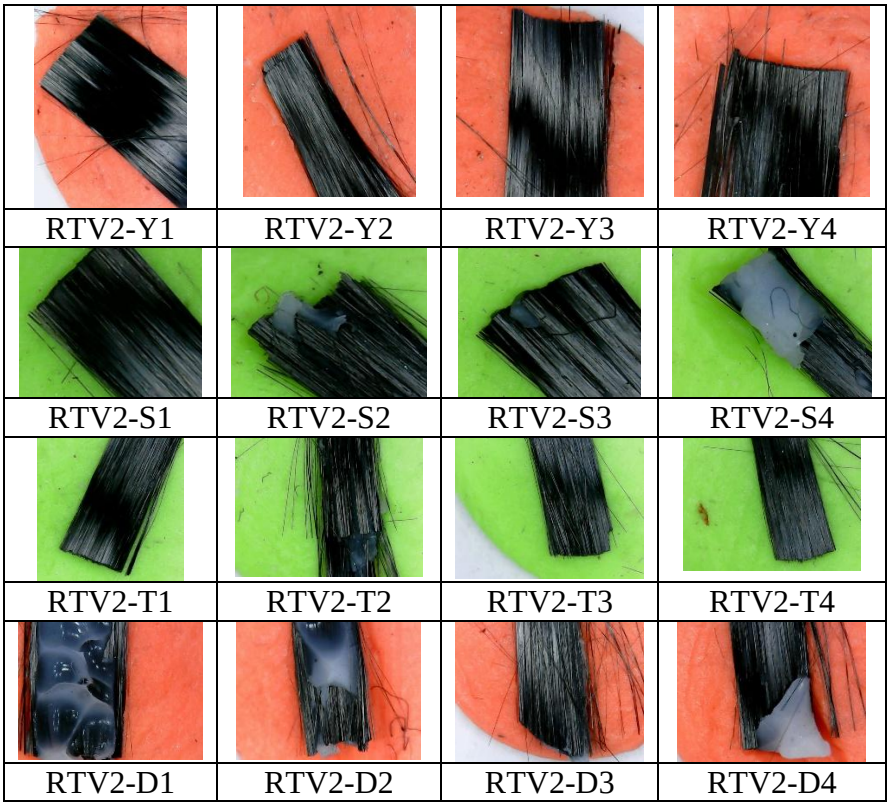

Figure 3. Image of each fiber tow end embedded in silicone.

4. Conclusion

This experimental procedure is set up to see reaction of different additives into silicone in terms of interfacial shear strength between silicone and carbon fiber tow. Both pull-out test results and optical images illustrates that dichloromethane addition elevates interface strength and adhesion capability of silicone onto carbon fiber. Despite reducing the viscosity, other additives cannot raise strength. In future studies, other additives can be tried with different kind of fibers.

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