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Impact and Tensile Properties of Alkaline Treated Textile Fibre Reinforced Polymer Composites

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Abstract: Alkaline treatment's effect plays a vital role in determining textile fibre reinforced polymer materials' mechanical properties. This study's primary concern was to obtain the optimum concentration of alkali solution affected by textile fibre reinforced polymer composite's mechanical properties under impact and tension loading. The textile fibre was treated with an alkali solution known as sodium hydroxide (NaOH) with distinct weight percentages (1, 3, and 5wt%). The low-velocity impact test (ASTM D7136) and tensile test (ASTM D3039) were conducted to analyse the tensile and impact properties of untreated and treated composite specimens. All specimens prepared in this research were the end products of the compression moulding process. The tensile strength and impact resistance result improved when textile fibres were treated with 1wt% NaOH solution based on the tensile and impact test results.

Keywords: Fibre treatment, drop weight impact, sodium hydroxide, tensile, textile waste

1. Introduction

Malaysia is a developing country with an annual population increase, with an estimated population of around 32.8 million in 2020, exceeding 40 million marks in 2045. With current population speed growth, there has been a daily increase of 47,218 tonnes per day in municipal solid waste. The total amount of solid waste produced by households is 65%, while an industry with commercial and institution is around 16%. Other waste produced, including textile, glass, metal, e-waste, and hazardous household waste (Malaysia's Performance Management And Delivery Unit (PEMANDU), 2015). It could be a challenging task for Solid Waste and Public Cleansing Management Corporation (SWCorp) to properly dispose of municipal solid waste with the current population without harming the environment.

The attention towards cotton fibre reinforced polymers has recently increased due to their excellent cotton fibres properties. To name a few, cotton can be decomposed naturally, having desirable physical properties, and cheaper than other fibres. Virgin cotton not to include clothing and attire, has made an impact of achieving global trade of up to 67.9 billion US Dollar. Without a doubt, this milestone has set cotton as the most well known natural fibre in this era. There are numerous applications to harness the benefits of cotton in the modern industry. To highlight a few, cotton fibres of different forms were utilised as reinforcement in composites as well as in manufacturing geotextiles. (Gindl-Altmutter et al., 2012).

The critical issue in implementing natural fiber composites is the fibre-matrix interface properties that appear to be the limiting factors regarding composite structural integrity. An alternative has been proposed by chemical modification of which alkaline treatment to be implemented. Unfortunately, treating fibre with alkali will inevitably swell the fibres with excessive moisture absorption, which is detrimental to the particular composite's dimensional stability (Rowell & Sanadi, 2014). This treatment aims to release the clumped plant fibres into singled out fibres, creating more surface of contact and high friction surfaces, which improves the interactions of fibre/matrix. Chemical compositions of the fibres are affected because of the removal of hemicelluloses, pectins, and wax. Alkaline treatment is directly influencing the incremental change of the degree of crystallinity on the cell wall's cellulose at any concentrations. Both dilute and concentrated alkaline treatment can improvise the fibre and matrix interfacial properties with regard to the matrix's overall behaviour.

Nevertheless, the fibres' damage may exceed any benefit achieved by the high concentration of alkaline treatment (Jones et al., 2017). An abundance of researchers from past studies utilise varying concentrations of alkaline solutions as well as a myriad of immersion durations. Past researches have shown that a 1% NaOH solution contributes to cotton fibre properties, both mechanically and physically (Koyuncu et al., 2016). Both properties correspond to the alteration upon the interface. To make it clear, alkaline treatment specifically increases surface roughness and cellulose on the exposed parts of each individual fibre. Hence, the idea is to treat cotton fibres with NaOH alkaline solution to achieve the desired attributes.

During this experiment, textile waste from the cotton fibres was treated with three different concentrations of NaOH (1, 3, and 5wt%). The untreated and treated textile fibre reinforced polymers were then prepared via the compression moulding technique. The mechanical properties of the composites were examined under impact and tension loading.

2. Materials and Methodology

2.1 Materials

A pre-consumer textile waste from the cotton fibre was used as the reinforcement material, while a Miracast 1517 epoxy resin supplied by Miracon (M) Sdn. Bhd was used as the matrix material. Sodium hydroxide (NaOH) was used in this study as the alkaline solution. Sodium hydroxide pellets (~99% purity) was purchased from Merck (M) Sdn Bhd, Selangor, Malaysia.

2.2 Methodology

2.2.1 Alkaline treatment

Alkaline treatment was conducted on cotton fibres using a NaOH solution with three different weight percentages (1, 3, and 5wt%). The fibres were soaked and stirred using mechanical stirrer for two hours at ambient conditions (22˚C and 1 atm). After treatment, the fibres were rinsed several times with fresh tap water and several drops of acetic acid until the fibres neutralise to pH7, eliminating any remnants of sodium hydroxide solution. Then, the fibres were dried in the oven at 105°C for 48 hours. The fibres once again oven-dried at room temperature for another 6 hours to ensure the fibres were dried entirely.

2.2.2 Composite preparation

The cotton fibre used in the composite materials' fabrication process was crushed to fine fibre with a grinding machine. 6 wt% of the cotton fibres were mixed with the epoxy resin and poured into the silicon rubber mould. The composite specimens were prepared by a compression moulding technique. After the specimens were completely cured, the excess resin from the edges was trimmed out.

2.3 Testing

2.3.1 Density Test

The density test for cotton fibre reinforced polymer (CFRP) specimens was carried out using the Archimedes principle. Density is very much useful for calculating the strength-to-weight and stiffness-to-weight ratio of the composite.

2.3.2 Tensile Test

Fabricated composite specimens went through a tensile test in accordance with ASTM D3039. The specimen of 250 mm × 25 mm × 2.5 mm, were tested using the universal tensile testing machine (Shimadzu AG-IS 50kN) with 5kN load cell at a constant speed rate of 2 mm/min.

2.3.3 Drop-Weight Impact Test

The specimens underwent the drop-weight impact test abiding ASTM D7136. The test was performed utilising an Instron Dynatup 8250 Drop Weight tester equipped with a 12 mm diameter hemispherical tip impactor with a mass of 6 kg and 10 J impact loading. The specimen's geometry utilised in this test was 50mm × 50mm × 5 mm.

3. Results and Discussion

3.1 Density measurement of CFRP specimen

The untreated and treated fibre reinforced composites' density was measured, the results of which are presented in Table 1. The 1wt% NaOH treated fibre has the highest density value of 1.183 g/cm^3 relative to the 5wt% NaOH treatment specimen with the lowest density value, with only 1.158 g/cm^3.

Therefore, higher concentration alkaline treatment to fibre reduces the composite density when pectin, wax, and impurities from the fibre are removed (Ren et al., 2019). NaOH treatment may cause a higher swelling and completely transform the existing lattice from cellulose-I to cellulose-II (Maya Jacob John, 2008). The weight reduction of the cotton fibre resulting from alkaline treatment can be clarified by the significant reduction in fibre diameter due to hemicellulose dissolution (Rokbi et al., 2011). Nevertheless, when the NaOH concentration was 3wt%, the average density was not significantly increased. The fibre's swelling effect has exceeded the optimum level related to the breakage of the hydrogen bond.

Table 1. The average value for weight and density of all composite specimens

Composite Specimen	Average Weight, (g)	Average Density, (g/cm^3)
Untreated	16.09	1.168
1wt% NaOH	16.68	1.183
3wt% NaOH	16.14	1.168
5wt% NaOH	16.06	1.158

3.2 Tensile properties of CFRP composite

The typical graph of tensile strength versus tensile strain of untreated and treated CFRP is illustrated in Fig. 1. As shown in Table 2, at 1wt% of NaOH treatment, the optimal tensile strength was observed to reach the value of 4.433 MPa with a 57.4% improvement compared with untreated fibres. Nevertheless, the tensile strength of CFRP decreased to 2.52 MPa after 5wt% of NaOH treatment. This reduction was 10.5% less than the untreated fibre. This may be considered due to excessive NaOH solution that damaged the cellulose structures in the fibres and degraded the macromolecular chains of cellulose into short molecular chains and microcrystalline structures. Since the load-bearing components are cellulose (cotton fibre), their degradation affects the tensile strength of cotton fibre accordingly (Li et al., 2007). The strength suddenly drops at higher concentrations solution after maximum tensile properties are attained at a percentage of 1wt% of NaOH.

Table 2. Tensile properties of all composite specimens

Tensile Properties	Composite Specimen			
	Untreated	1wt% NaOH	3wt% NaOH	5wt% NaOH
Tensile Strength, (MPa)	2.815 ±0.115	4.343 ±0.155	3.576 ±0.203	2.520 ±0.332
Tensile Strain, (%)	1.350 ±0.11	1.962 ±0.112	1.7548 ±0.123	1.565 ±0.0615
Tensile Modulus, (GPa)	2.082 ±0.0486	2.219 ±0.152	2.044 ±0.167	1.612 ±0.177

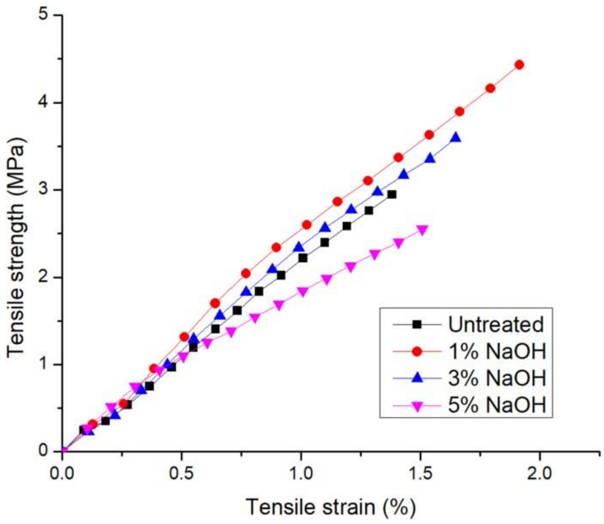

Fig. 1. Typical stress-strain graph of all composite specimens

An enhanced or decline of adhesion interface between fibre and matrix may cause improvement or regression of adhesion interface (surface damage) done by alkaline treatment to the treated cotton fabric. Alkaline treatment with 1wt% NaOH concentration enhanced the tensile properties of CFRP composites is due to the improved wetting ability of the alkali-treated fabric with the matrix (Koyuncu et al., 2016). Rougher topography at the fabric's external surface resulted from an alkaline treatment that eliminates the hemicellulose, lignin, and wax from covering the fabric. Thus it increases the mechanical interlocking of fabrics in the matrix and interface quality (Van de Weyenberg et al., 2006). The fibre split after alkaline treatment (fibrillation) breaks the untreated fibre bundle down into smaller ones through a hemicellulose breakdown. The fibrillation encourages more surface contact with the matrix, thus enhancing the interfacial bonding (Bachtiar et al., 2010). However, the content of hemicellulose and lignin in this system decreased after alkaline treatment, thus the oriented cellulose fibres efficacy improved. Enhanced fibre dispersion in the matrix caused by alkaline treatment, leading to an increase in the fabric aspect ratio. This improvement resulted in increased fabric reinforcement efficiency and hence the strength of composite increased (Hamdan et al., 2017). Decreasing the amount of stress concentration transferred to the fibre as the fibre size in the matrix decreased, which resulted in an increase in strength. Nevertheless, the fibre's contact area with the matrix increases with increased interaction between the fibre and matrix (Liu et al., 2004).

Table 3 shows that the values of specific tensile strength and specific modulus for the CFRP composite indicate the optimum concentration of alkali that can enhance the specimen's tensile properties. It is obviously seen that at 1wt% alkaline treatment, composite specimen projects the highest specific tensile properties. The value of the 1wt% NaOH composite specimen's specific strength appears to be 52% higher than the untreated composite specimen's specific strength. For the specific modulus value, 1wt% NaOH composite specimen recorded a 5% increment compared to the untreated composite specimen.

Table 3. The specific strength and specific modulus values of all composite specimens

Specimens	Specific Strength, (MPa/gcm^{-3})	Specific Modulus, (GPa/gcm^{-3})
Untreated	2.410±0.194	1.783±0.072
1wt% NaOH	3.671±0.101	1.876±0.073
3wt% NaOH	3.062±0.132	1.750±0.080
5wt% NaOH	2.176±0.217	1.392±0.040

The tabulated data shows a simple scatter plot was constructed to illustrate the properties of all untreated and treated CFRP specimens in this study. Fig. 2 represents the specific strength against the specific modulus of all untreated and treated CFRP specimens.

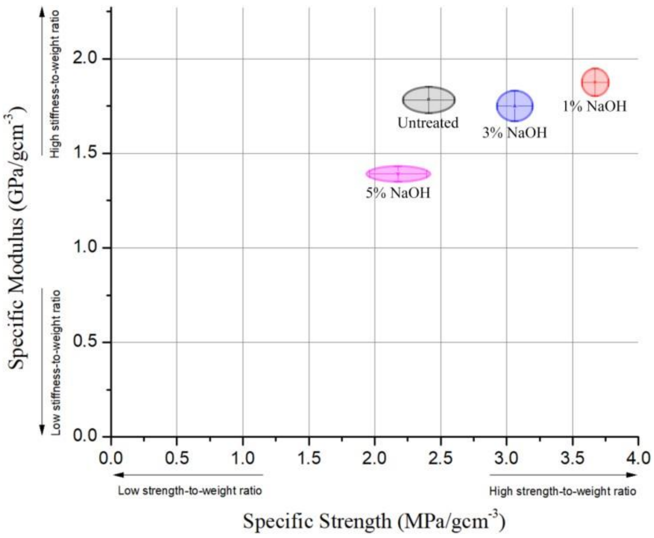

Fig. 2. The specific modulus versus specific strength of CFRP composites

3.3 Impact properties of CFRP composite

Impact test can be used to determine a specimen's amount of load, maximum load energy, and total absorption energy. The determination of the optimum concentration of alkali treatment (NaOH) on cotton fibre was analysed according to the composite specimen's impact resistance properties. The transient responses were recorded in terms of load, energy, and deflection properties obtained from the low-velocity impact test. The load versus deflection (Fig. 3) and load energy versus time responses (Fig. 4) for CFRP composite specimens were plotted at the 10J impact energy level. Table 4 shows the recorded information regarding impact parameters and energy-absorbing properties such as peak loads, deflection at peak loads, initiation energies, propagation energies, impact energies, ductility indexes, impact strength, specific impact strength, and specific total energy absorbed.

Table 4. Impact parameters of all composite specimens

Specimens	**Untreated**	**1wt% NaOH**	**3wt% NaOH**	**5wt% NaOH**
Peak Load (kN)	1.123	1.246	1.133	1.202
Deflection at peak load (mm)	0.5865	2.375	2.210	0.953
Initiation Energy (J), E_m	0.2923	1.7998	1.6894	0.4359
Impact Energy (J), E_i	9.7011	9.7315	9.3651	9.234
Propagation Energy (J), E_p	1.6757	2.7964	1.4173	2.471
Ductility Index	5.733	1.554	0.839	5.669
Impact Strength (kJ/m^2)	2.584	14.938	15.914	3.854
Specific Impact Strength (kJ.m/kg)	0.00213	0.0137	0.0128	0.00326
Specific Total Energy Absorbed (J.m^3/kg)	0.00162	0.00397	0.00266	0.00246

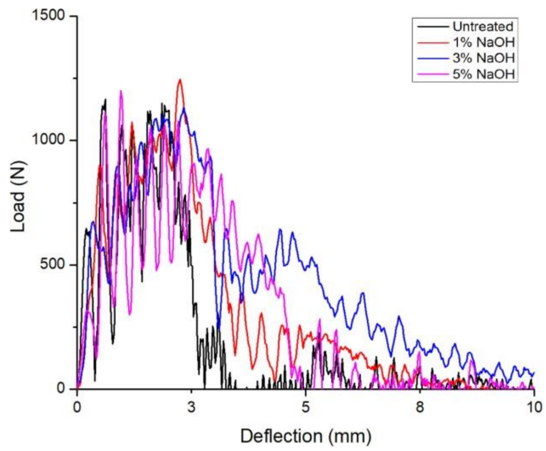

Fig. 3. Typical load versus deflection curve of all composite specimens

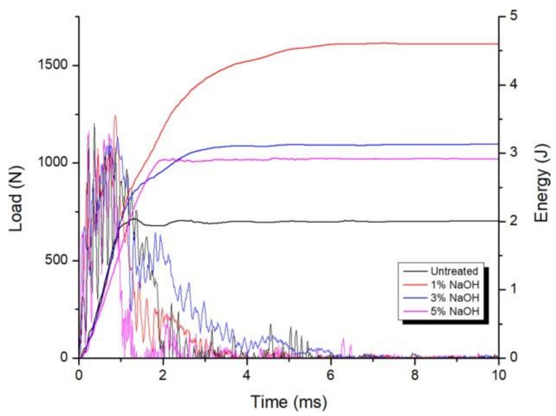

Fig. 4. Typical load-energy versus time curve of all composite specimens

From Fig. 3, higher damage load was detected from 1wt% of NaOH CFRP composite specimens at 1.246 kN. The impact properties of composites showing trend improved at 1wt% of NaOH compared to untreated specimens. The maximum load indicates a decreasing trend after 1wt% NaOH. The maximum damage load can be sustained by specimens decrease by 9% for concentration 3wt% of NaOH. Fig. 4 indicates that the energy to maximum load decreased in the trend that the composite can sustain after abrupt increase energy to maximum load for specimens of 1wt% NaOH. An increase of ductility behaviour for 1wt% of NaOH specimens showed that the composite having a tougher surface and has better adhesion between fibre and matrix than untreated CFRP composite. The total energy absorbed after the optimum level of alkaline treatment decreased as the concentration level increased. From the observation, composites made from fibres treated with NaOH have a higher impact resistance than composites made with untreated fibres. CFRP composite with 1wt% of NaOH treatment recorded the highest peak load and maximum initiation energy compared to other specimens. It indicated high load capacity as it can absorb more load and the high energy needed to inflict damage. The force applied is transmitted directly by the matrix and transferred to the fibre through a fibre-matrix interface (Bajerlein, 2011). The lowest peak load was recorded on 3wt% of NaOH, due to less interpenetration between the matrix and the fibre surface.

The impact strength value calculated for CFRP composite revealed that 1wt% of NaOH specimen presents the highest value. This means 1wt% of NaOH specimens has more damage resistance during impact. The marker is also known as the specific total energy absorb measurement. It measures the weight efficiency of an absorber material concerning weight and specific impact strength, which measures the efficiency of strength in weight. Among the CFRP composites, 1wt% of NaOH specimens obtained the highest value of strength-to-weight ratio and specific energy absorbed-to-weight ratio. This denotes that 1wt% of NaOH specimen is more effective absorbers and better resistance to damage concerning its weight. Fig. 5 observed a high strength-to-weight ratio, and high energy-to-weight ratio was recorded for 1wt% of NaOH compared to untreated specimens, resulting in the positive effect of alkaline treatment on cotton fibre textile waste.

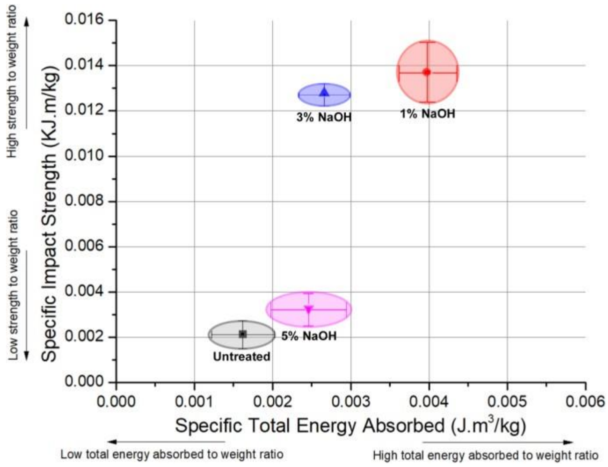

Fig. 5. Specific impact strength versus specific total energy absorbed of CFRP composite

3.4 Damage observation of specimens

Damage observations upon all of the specimens are provided in Fig. 6. A clearer picture of the damaged specimens was taken in close detail to display and identify the composite's fractured surface.

From the damage pattern observation of impact specimens, the deformation on specimens' surface was evaluated based on crack and brittle behaviour. The observation demonstrates that the damaged area and brittle fracture increases if the fibres are damaged by alkaline treatment or no bonding between fibre and matrix. The treated fibre of 1wt% NaOH shows fewer cracks on the surface than an untreated specimen, while 5wt% NaOH specimens are more of a larger fractured display. The damaged surface of 5wt% NaOH specimen thus confirmed that a higher concentration of alkaline damaged the fibre. This indicates that the treated fibre with 1wt% of NaOH increases the adhesive bonding of fibre and matrix.

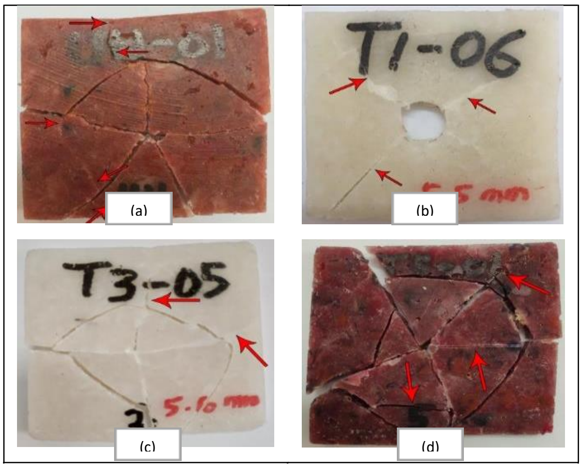

Fig.6. Visual observation of
(a) untreated, (b) 1wt%, (c) 3wt% and (d) 5wt% of CFRP specimens
(arrows indicate crack propagation)

4. Conclusions

CFRP composites were fabricated with a compression moulding method treated with different concentrations of the alkaline solution. The effects of alkaline treatment on cotton fibres were investigated from the mechanical perspectives. The alkaline treatment of cotton fibres improved their mechanical interlocking between the fibres and the epoxy matrix. The tensile strength and tensile modulus increased by up to 57.4% and 6%, respectively, at 1wt% NaOH, which optimal concentration of alkaline treatment for cotton fibre. For the low-velocity impact test conducted, the impact load and other impact parameter values depended on the impact energies. Improvement in loading capability and the toughest characteristic displayed on 1wt% of NaOH CFRP composites such as higher value in peak load, maximum initiation energy, high impact strength, high strength-to-weight ratio, and high total energy absorbed-to-weight ratio. From the observation of damage fracture behaviour, more extensive crack propagation was observed at 5wt% NaOH specimen. At optimum concentration, which is 1wt% of NaOH, displayed less crack propagation around the impacted surface due to enhanced mechanical interlocking between fibre and matrix. These results suggested that lower concentration alkaline treatment does increase the performance of the cotton fibre.

5. Acknowledgements

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