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# Mechanical Behaviour of AA 6061–$Ca_2SiO_3$ Composite

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## ABSTRACT

The advantage of composite materials over non-alloy/virgin metals has been on the front burner in the engineering materials sphere. To this ends, various reinforcement materials are constantly been mixed with metal matrix to form new composite materials. $Ca_2SiO_3$ is a ceramic material which finds application in medicine, heat and noise insulation, acid remediation, cement production etc. since it possesses qualities needed for the formation of composites, and is largely not researched on, this study aimed to characterize the mechanical properties of the AA 6061 - $Ca_2SiO_3$ composite for different composition of percentage mix, and to establish a model that would predict the UTS for known values of percentage mix and load. Result of the study shows that 6% $Ca_2SiO_3$ – 94% AA 6061 and 24% $Ca_2SiO_3$ – 76% AA 6061 possessed the highest modulus of elasticity and are stiffer while 2% $Ca_2SiO_3$ – 98% AA 6061 mix had the lowest modulus of elasticity, and is more ductile than other composition mix. Also, it was observed that addition of $Ca_2SiO_3$ to AA 6061 T4 greatly improves its mechanical properties and96.43% of the variations in stress experienced by various percentage composition of the composite mix can be explained by the developed model.

***KEYWORDS:*** *Characterization, Composite, Modelling, Aluminium, Calcium Silicate*

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## INTRODUCTION

The material industry in recent times has been experiencing a lot of changes as new materials are being formed/modified to match up with the ever changing material requirements of this technological age. A contributing factor to this development is the benefits inherent in composite materials. It has been generally proven that two or more materials which possess different physico-chemical properties are combined; the end material is usually an improvement on the properties of the individual parent materials. In the broad classification of Engineering materials, metals are the most commonly used class [1 – 2] mainly due to the desirable properties they possess. For instance, Aluminium finds wide application in power lines, high-rise buildings, window frames, consumer electronics, industrial and household appliances, aircraft components, spacecraft components, roofing sheets, ships, trains, etc.

Although Aluminium has excellent chemical, physical, and mechanical properties such as corrosion resistance, low density, non-toxic, high-strength to-weight ratio [3], it is often times used as an alloy because it is not particularly strong [3]. The alloying material will be chosen based on the new material requirement in line with the condition of the environment/factors the material will be subjected to during its life time/ service period. For metal matrix composites, the alloying material is usually a ceramic which act as a reinforcement embedded in the metal matrix phase. In this combination, the matrix transfers the load exerted on it to the reinforcing element, thereby increasing the load bearing capacity of the composite. Reinforcement materials used in Aluminium composites (AMC) are basically carbides, Oxides, or Borides such as $Al_2O_3$, $TiB_2$, $TiO_2$, SiC, TiC, $B_4C$ etc. [4]. Other materials include fly ash, [5], red mud[6], borate whisker, and have all been proven to improve the material properties of Aluminium such as relative density, hardness and tensile strength [7]. For instance, in a study carried out by Prabhuet. al. [8], where $TiO_2$ was used to reinforce Al6061, $TiO_2$ was added by 1% - 4% by weight fractions with increment of 1%. Result of the research showed increase in hardness as a result of the addition of $TiO_2$. Addition of $TiO_2$ increased the hardness by 15%, 24%, 36%, and 44% respectively. The ultimate tensile strength had a maximum increment value of 14% at 3% composition of $TiO_2$. Qudeiriet. Al. [6] noted that when 8 wt% reinforcement of $Fe_2O_3$ is added to Al 6061, it increases the hardness and UTS by 30% and 25% respectively when compared to unreinforced Al 6061. Ravirajet. al. [8] noted that addition of TiC prominently refines the graun structure of the composite and also increases the strength. Kandpalet.al.,[9] while working on AA6061-$Al_2O_3$ composite introduced 5% - 20% of $Al_2O_3$ in 5% increments and revealed that both hardness and UTS increased with increment in $Al_2O_3$ showing that the mechanical properties of AA 6061 are greatly influenced by reinforcement composition. Li et. al., [10] while working on fabrication and characterization of stir casting AA 6061-31% $B_4C$ composite revealed AA 6061 – 31% $B_4C$ composite had UTS of 340 MPa, signifying an improvement in virgin AA 6061 by 96.5%. Moses et.al.[11]fabricated an AA 6061 – SiC composites with 5%, 10% and 15% of SiC weight fraction as reinforcement of the 3 samples of the composite. The result showed that composite with 15% of weight fraction had 133.33% higher microhardness and 65.2% higher ultimate shear strength compared to unreinforced AA 6061 alloy. Vanarotti[12] while characterizing an AL 356 – SiC composite noted increase in SiC increases the hardness of the composite when compared to the unreinforced Al 356.

**Aluminium alloy and other reinforcements**

Gladston et.al., [13] Prasad and Krishna [14] in their works all agreed that increase in rice husk increases the hardness of Aluminium matrix, and also increases the UTS when 15% weight fraction of rice husk is added to Aluminium matrix. Glass has also been used to reinforce AA 6061, one of such a research was carried out by [15] where composites were prepared by adding 3%, 6%, 9% and 12% of glass by weight fraction. It was observed that addition of glass reinforcement increased the number of dislocations, thereby restricting its movement and resulted in the increase of UTS by 61.3%. In a bid to promote cheap and easily available materials as composites, Chethanet. al.,[16] used bamboo charcoal as reinforcement material for AA 6061. 2%, 4%, and 6% eight fractions were reinforced into matrix respectively. Outcome of the research showed that increase in the reinforcement material increases the composite hardness and decreases the UTS when compared with the virgin alloy.

Most published works on AMCs centre on the use of reinforcement materials such as SiC, TiC $Al_2O_3$, $B_4C$, AlN, fly ash, Red mud, rice husk, corn cob, bamboo charcoal, and hybrid. The hybrid consist of an Aluminium matrix and a combination of more than one type of reinforcement material which could either be organic or inorganic as seen in the works of [17 – 27]. While the inorganic reinforcement offer improvement in the material properties of the matrix, high cost and complexities in synthesis routes pose a demerit to their wide scale use. On the other hand, the organic reinforcement could favour one mechanical property against another [16, 28, 29]. Major property requirements from reinforcement materials for AMCs include: high stiffness, hardness, compressive strength, lower thermal conductivity [30] etc. these properties are found in Calcium Silicate which has found wide acceptance in applications such as Endodontic treatment [31], bone replacement [32] heat insulation, fire protection and remediation of acid drainage [33], cement production [34]. However, with these properties possessed by $Ca_2SiO_3$, there is yet to be a Research carried on Al matrix – $Ca_2SiO_3$ composite. Hence this study has as its aim characterization of some mechanical properties of an AA 6061 – $Ca_2SiO_3$ and develops a model that establishes the relationship between stress value, load and various composition mix of the composite.

**Methodology**

AA 6061 T4 was used as the matrix material while $Ca_2SiO_3$ fibre was used as the reinforcement material. The elemental composition of AA 6061T4 and $Ca_2SiO_3$ fibre are given in table 1 while figure 1 shows the elemental analysis of the $Ca_2SiO_3$ sample using X-ray fluorescence spectroscopy.

**Table 1: Chemical Composition of AA 6061 Aluminium Alloy and $Ca_2SiO_3$**

| Element | AA 6061 T4 Composition (Mass %) | $Ca_2SiO_3$ Composition (Mass %) |
|---|---|---|
| Al | 98.58 | 8.75 |
| Mg | 0.28 | - |
| Si | 0.22 | 37.163 |
| Fe | 0.20 | 0.825 |
| Cu | 0.18 | 0.030 |
| Cr | 0.16 | - |
| Zn | 0.15 | 0.085 |
| Ti | 0.12 | - |

| | | |
|---|---|---|
| Mn | 0.11 | - |
| P | - | 0.365 |
| S | - | 0.727 |
| Ca | - | 51.05 |
| V | - | 0.005 |
| Co | - | 0.008 |
| Ni | - | 0.010 |
| Pb | - | 0.023 |
| W | - | 0.072 |
| Ag | - | 0.005 |
| Rb | - | 0.005 |
| Mo | - | 0.285 |
| Sn | - | 0.316 |
| Sb | - | 0.276 |

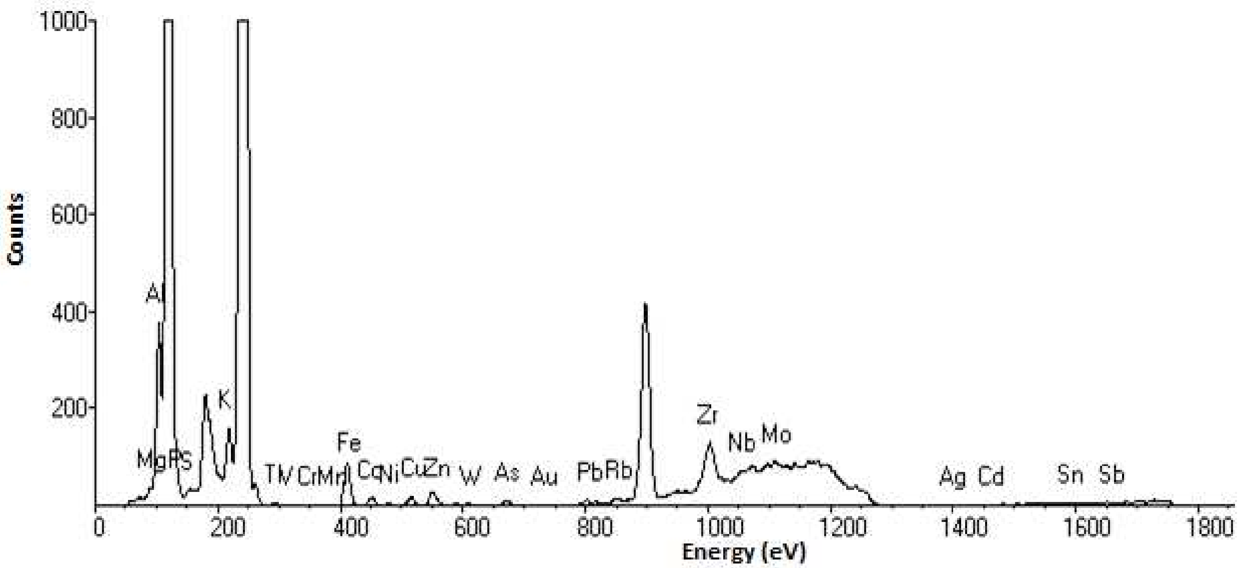



**Figure 1: Elemental analysis of a 37g $Ca_2SiO_3$ sample**

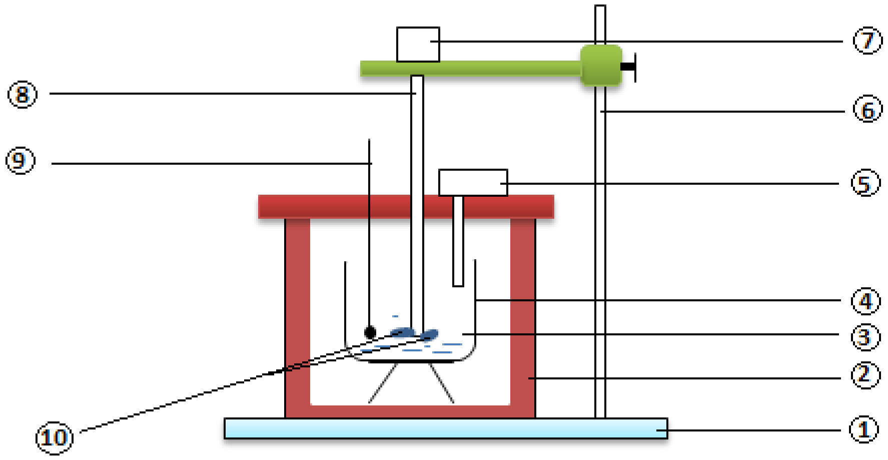
Stir casting method was used to produce the AA 6061-$Ca_2SiO_3$ composite whereby fine particles of $Ca_2SiO_3$ were dispersed in molten AA 6061 T4 matrix that was melted in a crucible electric induction furnace. Stirring was achieved through the aid of propeller blades that are attached to a shaft connected to an AC stepper motor which allows for varying rotational speed of the stirrer. Process parameters considered during the operation includes the following:

Reinforcement particle size: reinforcement particle size was considered because as stated by [35] strengthening effect is maximum when finer reinforcement particles are used. The fibre strands of $Ca_2SiO_3$ were processed to particle size of 500μm.

Stirring speed: the quality of distribution of the reinforcement material in the Al matrix is dependent upon the viscous nature of the matrix. A high viscosity is most likely to resist the ease of the reinforcement particle distribution, while a low viscosity will prevent particle retention within the matrix. This phenomenon makes the stirring speed important because inter-particle distance and homogeneity can be enhanced at higher stirring speed [6]. The stirring speed was set at 350rpm.

Stirring time: stirring is necessary for the effective distribution of the reinforcement and homogeneity of the mixture. Researches [36 – 37] have shown that specifying optimum value for stirring time is not practical since it varies with the shape of the stirring blade. However, the stirring time should be such that allows for a homogeneous mixture to exist. The stirring time at which a homogeneous mixture was achieved was 25 minutes.

Melting temperature: increase in melting temperature leads to a decrease in viscosity, which will not favour retention of particles in the matrix. Hence, the melting temperature was set at 580 °C which enabled agglomeration of the reinforcement particle to the matrix.Figure 2 shows a schematic diagram of the stir-casting method set up used in the production of AA 6061-$Ca_2SiO_3$composite.




1 – Base, 2 – Furnace, 3 – Molten AA 6061, 4 – Crucible pot, 5 – Disperse gun with Ca2SiO3, 6 – Stand, 7 – Variable speed electric motor, 8 – Stirring shaft, 9 – Thermocouple, 10 – Stirring blades

**Figure 2: A schematic diagram of the stir-casting method set up used in the production of AA 6061-$Ca_2SiO_3$ composite**

In order to obtain the regression model for AA6061-$Ca_2SiO_3$ composite, for tensile strength, the reinforcement material was added in percentages of 2% to 50% with 2% increment in percentage weight by mass. This yielded 25 samples which were produced and subjected to tensile and hardness testing using AMETEK-EZ250 and Teren TR-Y-HMG580 respectively as appropriate testing machines. The mass of each sample is 87g; gauge length is 25mm, gauge diameter of 3mm, grip diameter of 7mm.

**Result**

**Tensile test**

The tensile test shows that AA6061-$Ca_2SiO_3$ composite has UTS of 69.02 MPa at 2% composition of $Ca_2SiO_3$. Furthermore, significant changes in the UTS were observed to have occurred at 6%, 12%, 18%, 24% 30%, 36% and 42%. Beyond 42%, there was no significant change in the UTS of AA6061-$Ca_2SiO_3$ composite. Figures 3 to 10 shows the stress-strain curve for the various composition mixture of AA6061-$Ca_2SiO_3$ composite where significant changes were observed.

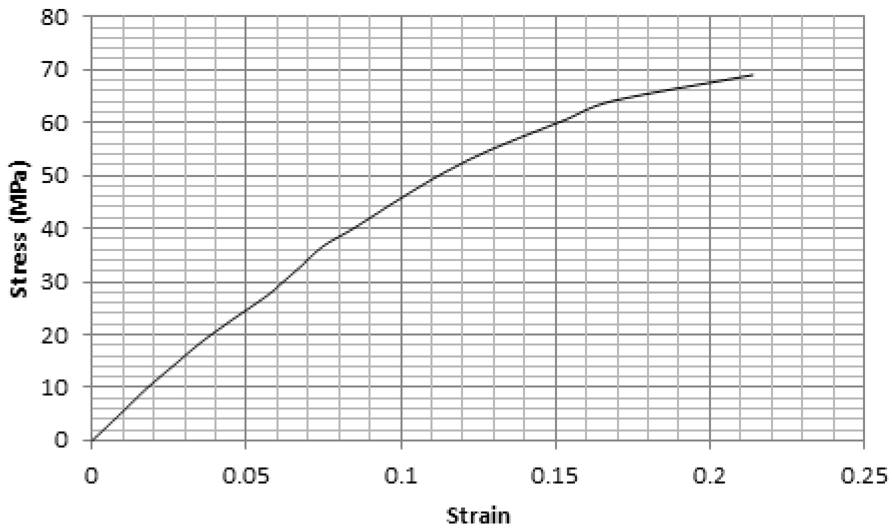



**Figure 3: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 2% $Ca_2SiO_3$ and 98% AA6061**

The stress-strain curve of AA6061-$Ca_2SiO_3$composite shown in figure 2 depicts a ductile material with UTS of 69.02MPa and strain of 0.214

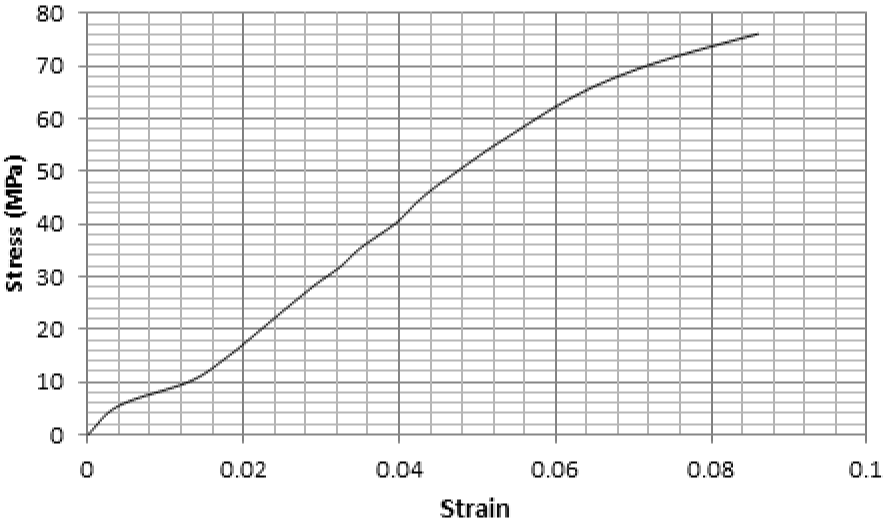



**Figure 4: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 6% $Ca_2SiO_3$ and 94% AA6061**

The curve in figure 4 shows that the composite UTS increased to 76.1 MPa which amounts to 10.26% increase from the 2%:98% mix. It is also observed that the material reduced in its ductility as the strain value declined from 0.214 to 0.086, suggesting that at this point, the material has recorded an increase in hardness, and is likely to be more brittle than 2%:98% mix.

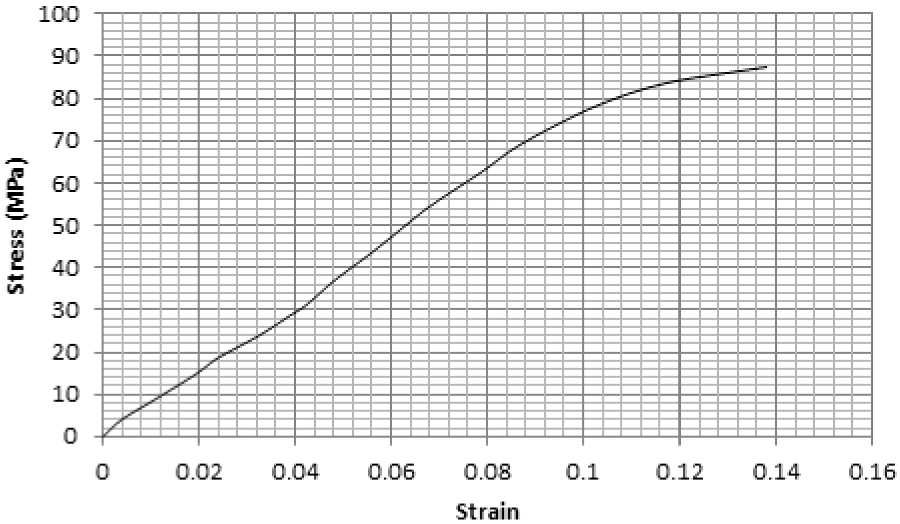



**Figure 5: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 12% $Ca_2SiO_3$ and 88% AA6061**

Figure 5 shows that the UTS of the composite increased to 87.41 MPa which amounts to 14.86% increase from the 6%:94% mix. The curve also shows that the composite is less ductile than 2%:98% mix since the strain value is 0.138, suggesting that the 12%:88% mix is more brittle than 2%:98% mix.

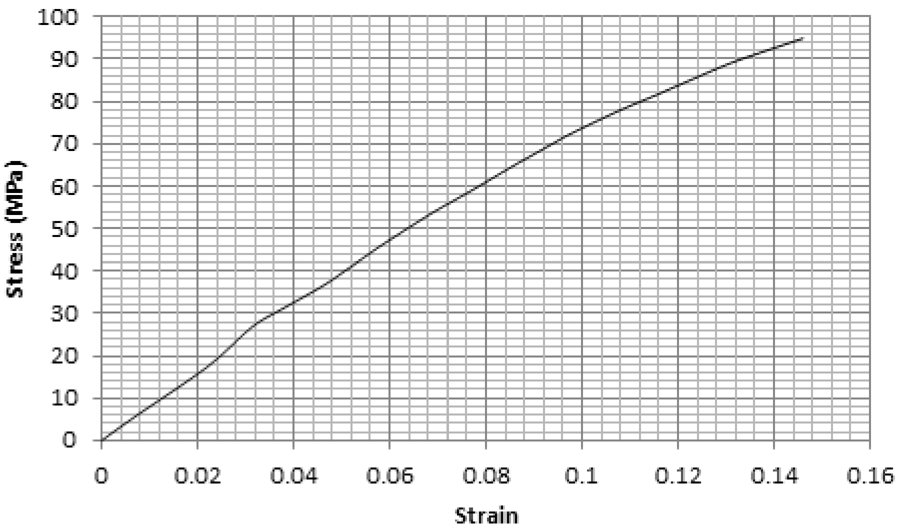



**Figure 6: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 18% $Ca_2SiO_3$ and 82% AA6061**

In figure 6, it is observed that the UTS of the composite increased to 94.91 MPa which amounts to 8.58% increase from the 12%:88% mix. The curve also suggests that the composite is less ductile than 2%:98% mix since the strain value is 0.146 hence, the 18%:82% mix is more brittle than 2%:98% mix.

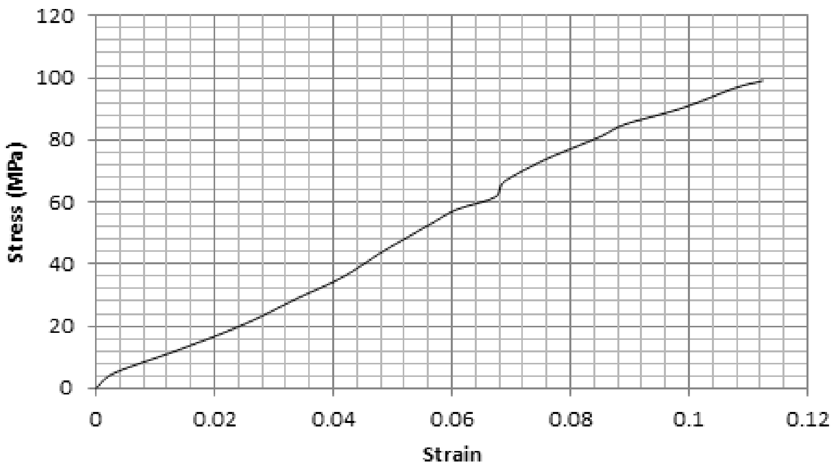



**Figure 7: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 24% $Ca_2SiO_3$ and 76% AA6061**

In figure 7, it is observed that the UTS of the composite increased to 99.01 MPa which amounts to 4.32% increase from the 18%:82% mix. From the curve, we observe that the material tends to yield at 60 MPa with a strain of 0.065. The curve also suggests that the composite is less ductile than 2%:98% mix since the strain value is 0.1124.

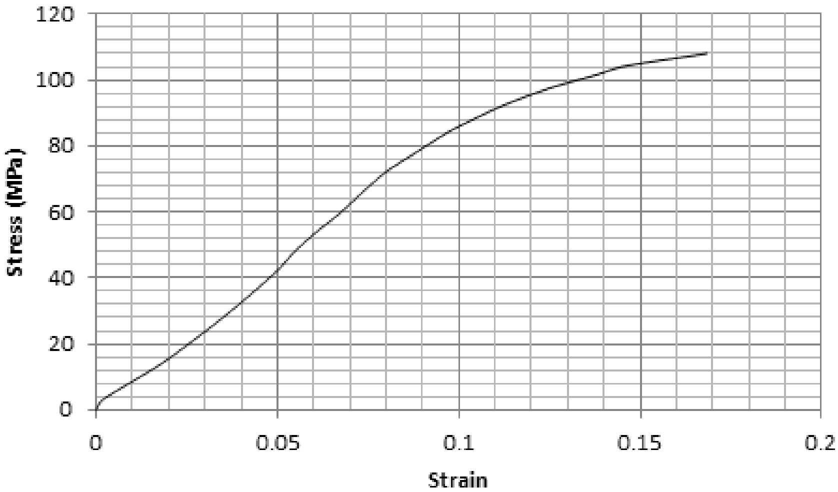



**Figure 8: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 30% $Ca_2SiO_3$ and 70% AA6061**

In figure 8, it is observed that the UTS of the composite increased to 108.06MPa which amounts to 9.14% increase from the 24%:76% mix. The curve also suggests that the composite is less ductile than 2%:98% mix since the strain value is 0.1684, but 5.8% more ductile than the 24%:76% mix.

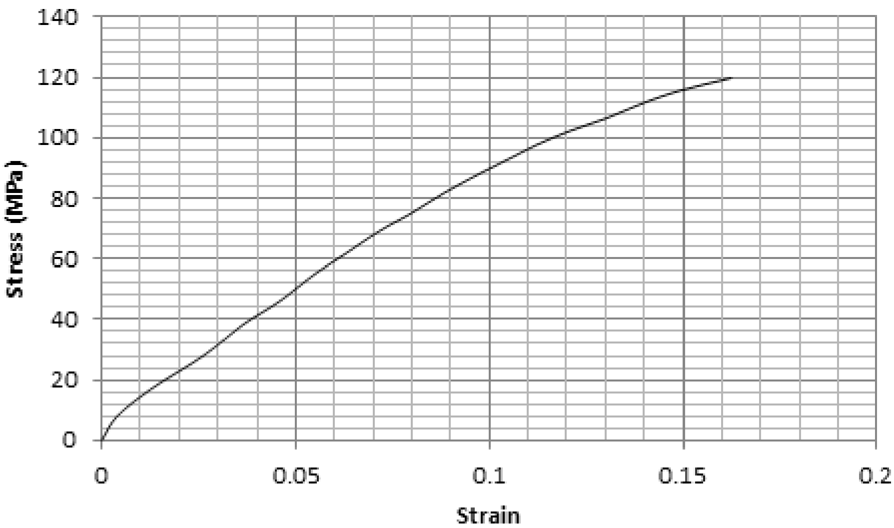



**Figure 9: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 36% $Ca_2SiO_3$ and 64% AA6061**

In figure 9, it is observed that the UTS of the composite increased to 119.06 MPa which amounts to 10.86% increase from the 30%:70% mix. The curve also suggests that the composite is less ductile than 2%:98% mix since the strain value is 0.1624, and it does not show any significant change in its strain value from that of the 30%:70% mix. This implies that load carrying capacity of the composite increased with negligible strain when compared to the 30%:70% mix.

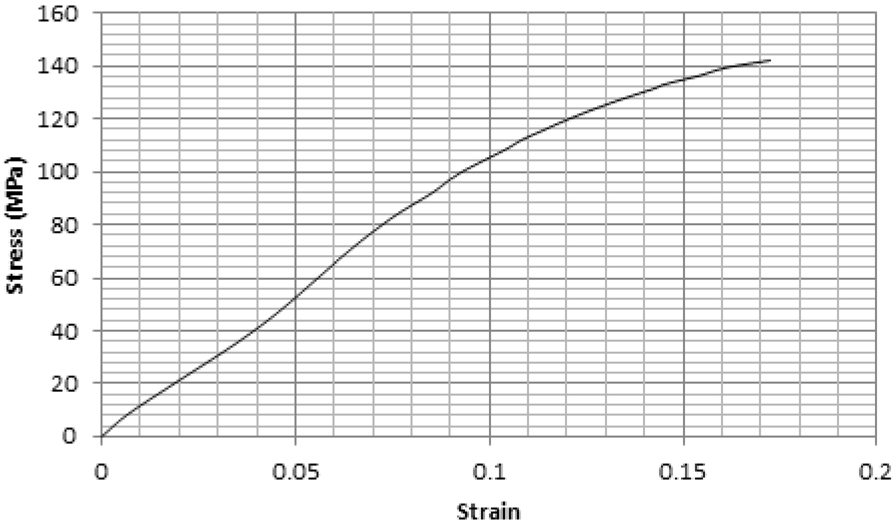



**Figure 10: Stress-strain curve of AA6061-$Ca_2SiO_3$ composite with 42% $Ca_2SiO_3$ and 58% AA6061**

In figure 10, it is observed that the UTS of the composite increased to 142.15 MPa which amounts to 18.66% increase from the 36%:64% mix. The curve also suggests that the composite is less ductile than 2%:98% mix since the strain value is 0.1724, and increases in strain by 1% from that of the 36%:64% mix. Beyond the 42%:58% mix, no significant change was observed in the tensile test result of the other mix.

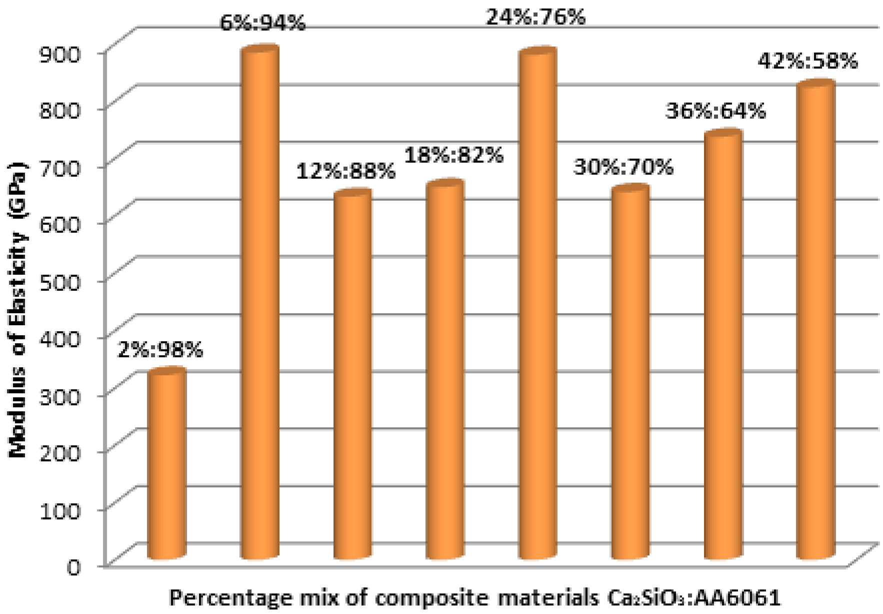



**Figure 11: Modulus of elasticity of AA6061-$Ca_2SiO_3$ with various percentage mix**

The modulus of elasticity for the various percentage mix of the composite is shown in figure 11. From the figure, it is seen that the 6%:94% mix and the 24%:76% mix possesses the highest ability to withstand elongation or compression with respect to length. This indicates that both mixes are stiffer than the other mixes, with the 2%:98% mix as the ductile of all the mixes. It also implies that both 6%:94% and the 24%:76% mixes can function effectively in very high corrosive conditions due to the low strain values recorded. This is so because the resistance to strain causes less deformation in the material thereby preventing corrosion inducing substances from permeating and reacting with the material. The steady increase in the modulus of elasticity from the 30%:70% mix to 42%:58% mix can be attributed to the significant increase, recorded in the load carrying capacity of the composite as the percentage of the reinforcement material increases as seen in figures 8 – 10. Also, the load to strain ratio increased significantly from 30%:70% mix to 42%:58% mix which could possibly be another reason for the steady rise in the modulus of elasticity.

**Hardness test**

The hardness test result also revealed that significant changes in the hardness occurred at 6%, 12%, 18%, 24% 30%, 36% and 42% addition of the reinforcement material. Beyond 42%, there was no significant change in the hardness of AA6061-$Ca_2SiO_3$ composite. Table 2 shows the result of the hardness value for the various percentage composition mixture of AA6061-$Ca_2SiO_3$ composite where significant changes were observed.

**Table 2: Hardness test result**

| %mix $Ca_2SiO_3$: AA6061 | 2%:98% | 6%:94% | 12%:88% | 18%:82% | 24%:76% | 30%:70% | 36%:64% | 42%:58% |
|---|---|---|---|---|---|---|---|---|
| **BHN** | 71.1 | 114.2 | 90 | 87.8 | 99.1 | 82.8 | 84 | 82 |

From table 2, it is seen that the 6%:94% mix has the highest BHN while the 2%:98% mix has the lowest BHN. This variation in hardness accounts for the changes observed in the strain of the individual composition mixes. Figure 12 comparative chart for the strain and BHN of the various composition mixes.

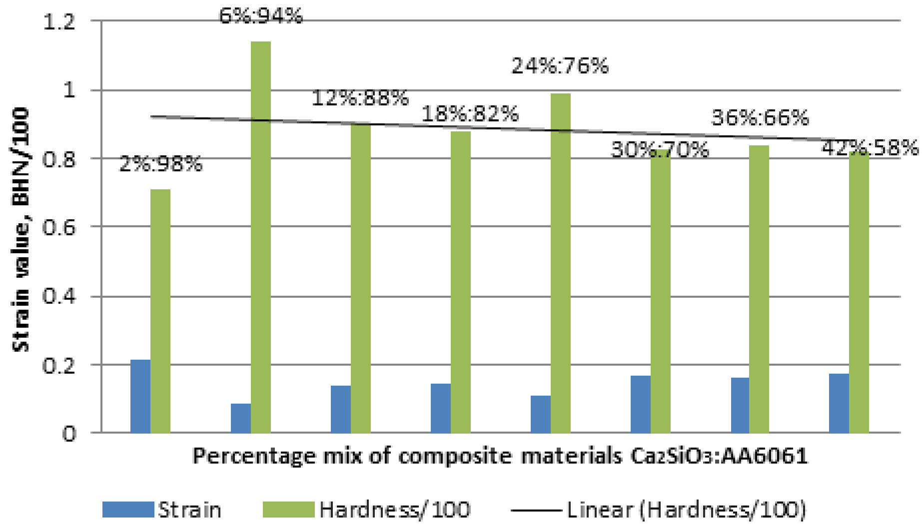



**Figure 12: Strain value vs BHN of the various percentage mix of AA6061-$Ca_2SiO_3$ composite**

From figure 12, it is seen that increase in hardness reduces the strain experienced by the material. Also, the trend line suggests that on the average, beyond the 6%:94% a decrease in the hardness is experienced. However, in general, when comparing the BHN of the various mix percentages to the BHN of AA6061 T4, it is safe to say that addition of the reinforcement material increases the hardness of aluminium while complementing on the corrosion resistance property of aluminium. Table 3 shows a summary of the mechanical properties results when compared with AA6061 T4.

**Table 3: Mechanical properties of AA 6061 and percentage mix of AA 6061-$Ca_2SiO_3$ composite**

| | AA 6061 T4 | Percentage mix of composite $Ca_2SiO_3$:AA6061 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2%:98% | 6%:94% | 12%:88% | 18%:82% | 24%:76% | 30%:70% | 36%:64% | 42%:58% |
| **BHN** | 65 | 71.1 | 114.2 | 90 | 87.8 | 99.1 | 82.8 | 84 | 82 |
| **UTS (MPa)** | 30 | 69.02 | 76.1 | 87.41 | 94.91 | 99.01 | 108.06 | 119.8 | 142.15 |
| **Modulus of Elasticity (GPa)** | 68.9 | 322.52 | 884.88 | 633.41 | 650.07 | 880.87 | 641.69 | 737.68 | 824.54 |

Table 3 shows that addition of $Ca_2SiO_3$ to AA6061 T4 enhances the mechanical properties of hardness, tensile stress and the modulus of elasticity. It also shows that there is a significant increase in the load carrying capacity, and load to strain ratio of the composite when compared to AA 6061 T4. This accounts for the high values of modulus of elasticity. Hence, this material will find application in designs where criteria such as stiffness, corrosion resistance, and strength are needed such as bicycle frames, vehicle chassis, utility boats, aircraft wings etc.

**Model development**

In order to establish the relationship between the amounts of stress experienced by the material for any given percentage mix and the operating load, a regression model was fit using the data obtained from the tensile test carried out for the various mixes ranging from 2%:98% to 50%:50%. The regression model is presented in equation 1.

$$\sigma_T = -83.83 + 214.7Al + 0.13511P - 133.5Al^2 \quad (1)$$

Where $\sigma_T$ = Stress, $Al$ = % of AA 6061 T4 in the mix, P = load

Equation 1 has a 5% level of significance, R-squared value of 96.43% and a p-value of 0.001. The model is accepted since the p-value < 0.05 which is the level of the model significance. Hence, 96.43% of the variations in stress can be explained by equation 1, and the equation can be used to predict the UTS for known values of percentage mix and load. It can also find the settings for AA 6061 or load for a desired UTS value.

**Conclusion**

In this study, some mechanical properties of various percentage mix of AA 6061-Ca2SiO3 composite (from 2% $Ca_2SiO_3$ – 98% AA 6061 to 50%Ca2SiO3 – 50% AA 6061) has been characterized. The values of these properties where compared with that of virgin AA 6061 T4, and the following conclusions were arrived at:

- Significant changes in the mechanical properties of UTS, strain, modulus of elasticity, and hardness exists for composite with the following percentage mix: 6% $Ca_2SiO_3$ – 94% AA 6061, 12% $Ca_2SiO_3$ – 88% AA 6061, 18% $Ca_2SiO_3$ – 82% AA 6061, 24% $Ca_2SiO_3$ – 76% AA 6061, 30% $Ca_2SiO_3$ – 70% AA 6061, 36% $Ca_2SiO_3$ – 66% AA 6061, and 42% $Ca_2SiO_3$ – 58% AA 6061.
- From a 42%$Ca_2SiO_3$ – 58% AA 6061 composite mix to a 50%$Ca_2SiO_3$ – 50% AA 6061, no significant change exists in the mechanical properties.
- Increase in the percentage composition of $Ca_2SiO_3$ in the composite mix will increase the UTS of the AA 6061-$Ca_2SiO_3$ composite. UTS is highest for 42%$Ca_2SiO_3$ – 58% AA 6061composition mix.
- 6% $Ca_2SiO_3$ – 94% AA 6061 and 24% $Ca_2SiO_3$ – 76% AA 6061 possessed the highest modulus of elasticity and are stiffer while 2% $Ca_2SiO_3$ – 98% AA 6061 mix had the lowest modulus of elasticity, and is more ductile than other composition mix.
- Increase in hardness of the composition mix reduces the strain experienced by the material, and beyond the 6% $Ca_2SiO_3$ – 94% AA 6061 mix, the hardness decreases with increase in the composition of $Ca_2SiO_3$.
- The hardness, UTS, and modulus of elasticity of AA 6061-$Ca_2SiO_3$ composite possess higher values than virgin AA 6061 T4.
- Addition of $Ca_2SiO_3$ to AA 6061 T4 improves its mechanical properties.
- As an area of further research, a microstructural study of 6% $Ca_2SiO_3$ – 94% AA 6061 and 24% $Ca_2SiO_3$ – 76% AA 6061composite mix should be carried out in order to understand reasons for the observed change in the trend of the mechanical properties characterized.

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