

SYNTHESIS AND CHARACTERIZATION OF FULLERENE FROM GRAPHITE ORE

Chit Chit Maw¹, Yi Yi Myint²

Abstract

This research work concerned with synthesis and characterization of fullerene from graphite ore. The graphite ore was collected from Thabeikkyin Township, Mandalay Region. The synthesis of fullerene was carried out by Modified Hummer's method in which graphite powder was oxidized with the help of oxidizing agent H₂SO₄ and KMnO₄. Moreover, the various amounts of NaNO₃, H₃PO₄, KMnO₄ and H₂SO₄ were used to produce fullerene. The crystal lattice size of graphite and fullerene were characterized by X-ray diffraction (XRD). The prepared fullerenes were analysed by Thermo gravimetric analysis (TG-DTA). The morphology of the graphite and the synthesized fullerene were investigated by scanning electron microscope (SEM).

Keywords: Graphite, Fullerene, Hummer's method, XRD, TG-DTA, SEM

Introduction

The prefix "nano" has found in last decade on ever-increasing application to different fields of the knowledge. Nanoscience, nanotechnology, nanomaterials or nanochemistry are only a few of the new nano-containing terms. The nanosized world is typically measured in nanometers (1 nm=10⁻⁹ m) (Hahens *et al.*, 2007).

Nowadays, nanotechnology research is developed as a cutting-edge interdisciplinary technology involving chemistry, physics, material science, biology and medicine (Roco, 2004). Nanomaterials and nanoparticles exhibit high strength, high thermal stability, low permeability and high conductivity properties, among other unique properties which stimulate the scientific commonly to focus their research on developing new applications and products related to nanotechnology. Nanoparticles are 1 nm to 100 nm in size. They have very small sizes and large surface area to volume ratios. Their atoms may also be arranged into tubes or rings. Carbon can form nanoparticle stimulates with a variety of shapes (Fears *et al.*, 2011).

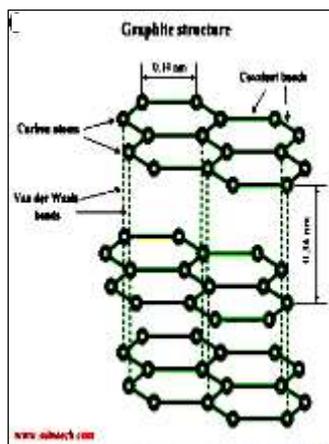
Graphite is a crystalline form of carbon, a native element mineral and one of the allotropes of carbon. Graphite is the most stable form of carbon under standard conditions. Graphite occurs in metamorphic rocks. Minerals associated with graphite include quartz, calcite, micas and tourmaline (Anthony *et al.*, 1990).

The fullerenes are the third allotrope of carbon after graphite and diamond. Each molecule of fullerene family (C_n) consists of 12 pentagons and m number of hexagons conforming to the relation $m = (n-20/2)$ (Euler's theorem). C₆₀ fullerene was produced from a graphite (Dietz *et al.*, 1981). The most abundant form of fullerenes is Buckminster fullerene (C₆₀) with 60 carbon atoms arranged in a spherical structure (Kratschmer *et al.*, 1990). It contains 12 pentagons and 20 hexagons. The pentagonal rings contain only single bonds (Hawkins *et al.*, 1991).

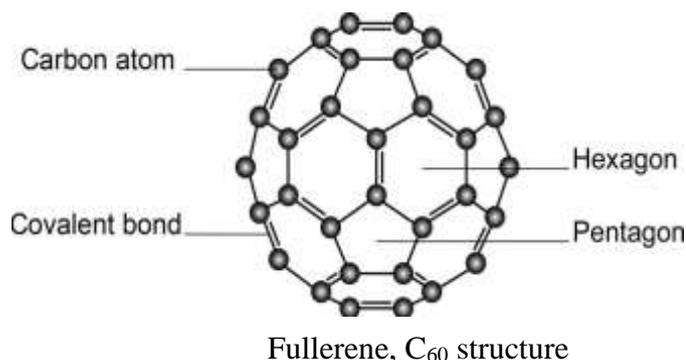
Fullerenes are used in a wide range of applications such as in optical and electronic devices (polymer additives, solar cells, photovoltaic) (Kronholm and Hummelen, 2007), in commercial cosmetic products (Xiao *et al.*, 2005), and in biomedicine (antiviral, anti-cancer, and antioxidant agents, in drug delivery systems) (Tagmatarchis and Shinohara, 2001). The aim of this research work is to synthesize and characterize fullerene from graphite ore.

¹ Lecturer, Department of Chemistry, Meiktila University

² Dr, Professor and Head, Department of Chemistry, University of Mandalay



Graphite structure

Fullerene, C₆₀ structure

Materials and Methods

Sample Collection

The graphite ore was collected from Thabeikkyin Township, Mandalay Region. The graphite ore was ground to get the powder. The graphite powder samples were stored in a well-stoppered bottle and used through out this research and presented in Figure 1.

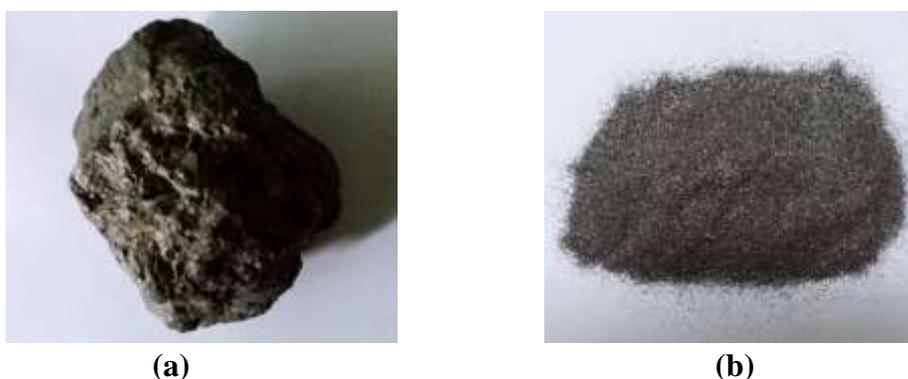


Figure 1 (a) Graphite ore (b) Graphite powder

Preparation of Fullerene from Graphite with NaNO₃, KMnO₄ and H₂SO₄ by Modified Hummer's Method under Different Conditions

Preparation of fullerenes (C-1) and (C-2) from graphite with NaNO₃, KMnO₄ and H₂SO₄

A 0.5 g of graphite powder sample and 0.25 g of sodium nitrate were mixed and stirred in ice bath by using magnetic stirrer. 20 mL of concentrated sulphuric acid and 2.0 g of potassium permanganate were added into the solution. The solution was stirred for 1 h. After stirring 1 h, this solution was removed from ice bath and again stirred for 3 h at room temperature. Then, 50 mL of distilled water was added into the solution and stirred for another 1 h at room temperature. 50 mL of hot water and 7.5 mL of 30 % hydrogen peroxide were added into the solution. The solution was stirred for 1 h at room temperature. Bright yellow color solution was obtained. This solution was centrifuged and the precipitate was collected and washed with 5 % hydrochloric acid and then with distilled water until it became neutral. Fullerene (C-1) was obtained.

The fullerene (C-2) was also prepared according to the same procedure as (C-1) preparation. However, the stirring time 3 h and sonication time 3 h were taken for preparation of C-2.

Preparation of Fullerene from Graphite with H₃PO₄, KMnO₄ and H₂SO₄ by Modified Hummer's Method under Different Conditions

Preparation of fullerenes (C-3) and (C-4) from graphite with H₃PO₄, KMnO₄ and H₂SO₄

A 0.25 g of graphite powder sample and 27 mL of concentrated sulphuric acid and 3 mL of phosphoric acid were mixed and stirred in ice bath by using magnetic stirrer. 1.32 g of potassium permanganate was slowly added to this solution and stirred for 1 h. After stirring 1 h, this solution was removed from ice bath and again stirred for 5 h at room temperature. Then dark green solution was obtained. 1 mL of hydrogen peroxide was added drop by drop and stirred for 0.5 h at room temperature. 10 mL of concentrated HCl and 30 mL of deionized water were added into the solution. This solution was centrifuged. The resultant precipitate was washed with 5 % HCl and distilled water until neutral. Finally, fullerene was obtained.

The fullerene (C-4) was prepared according to the same procedure of (C-3). However, the stirring time 9.5 h was taken for preparation of C-4.

Results and Discussion

Fullerene nanoparticles were synthesized from graphite ore by modified Hummer's method. The preparation of fullerene nanoparticles were performed under four different conditions. And the graphite ore powder and prepared fullerene nanoparticles were characterized by advanced methods such as XRD, TG DTA and SEM.

Characterization of Graphite Ore and Prepared Fullerene by XRD

The graphite ore powder was characterized by XRD and the chromatogram and results are presented in Figure 2 and Table 1-2. According to the results, the graphite sample shows a sharp peak ($2\theta = 26.141^\circ$) which corresponds to the diffraction line (002) with the intercellular spacing in the crystal (d) respectively is 3.4061. The range of particle size of graphite were found to be 152.76-855.98 nm and average particle size is 490.47 nm. Phase ID reported that graphite sample was graphite 2H. According to graphite grading HB scale, the collected graphite ore sample was found to be hard

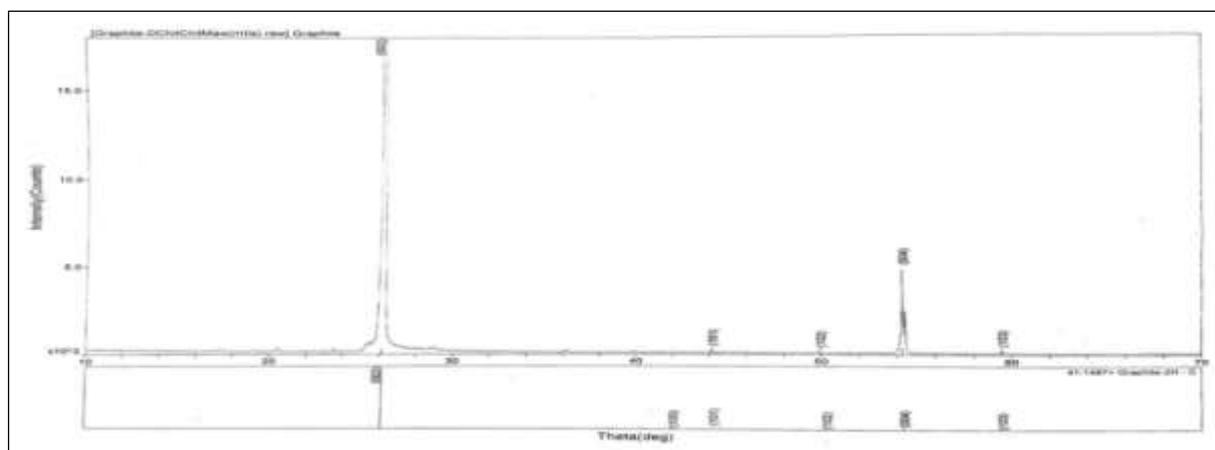


Figure 2 XRD diffraction pattern of graphite ore

Table 1 The Results from XRD Pattern of Graphite Ore

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | FWHM of peak (β) radians | Inter cellular spacing d (nm) | Particle size, D (nm) |
|----------|---------------------------|------------------------|----------------------------------|-------------------------------|-----------------------|
| 1. | 26.141 | 002 | 0.0018 | 3.4061 | 761.74 |
| 2. | 44.129 | 101 | 0.0034 | 2.0505 | 435.12 |
| 3. | 49.930 | 102 | 0.0099 | 1.8250 | 152.76 |
| 4. | 54.270 | 004 | 0.0018 | 1.6889 | 855.98 |
| 5. | 59.461 | 103 | 0.0064 | 1.5532 | 246.73 |

Table 2 The Peak ID Report of Graphite Ore

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | Area (%) | Phase ID |
|----------|---------------------------|------------------------|----------|-------------|
| 1. | 26.141 | 002 | 100.0 | Graphite 2H |
| 2. | 44.129 | 101 | 6.0 | Graphite 2H |
| 3. | 49.930 | 102 | 1.0 | Graphite 2H |
| 4. | 54.270 | 004 | 4.0 | Graphite 2H |
| 5. | 59.461 | 103 | 1.0 | Graphite 2H |

Fullerene nanoparticles were synthesized by using H_2SO_4 , $NaNO_3$, $KMnO_4$, H_2O_2 , HCl and H_3PO_4 under four different stirring times and shaking time. The highest yield of C-4 was 88.40 % followed by C-2, C-3 and C-1 as shown in Table 3.

Table 3 Yield Percent of Fullerene (C-1 to C-4)

| No | Fullerene | Yield (%) |
|----|-----------|-----------|
| 1 | C-1 | 73.02 |
| 2 | C-2 | 76.08 |
| 3 | C-3 | 74.52 |
| 4 | C-4 | 88.40 |

The prepared fullene (C-1 to C-4) were characterized by XRD and the results are presented in Figure 3-6 and Table 4-12.

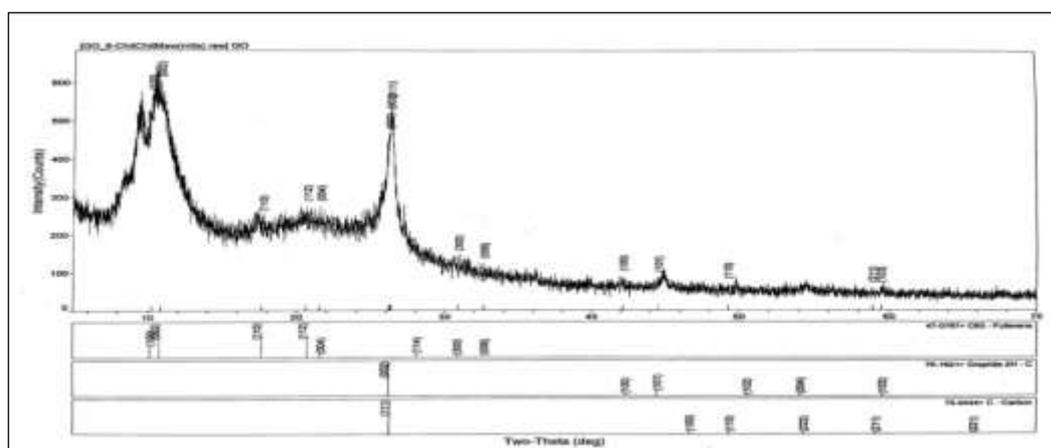
**Figure 3 XRD diffraction pattern of fullerene (C-1)**

Table 4 The Results from XRD Diffractogram of Fullerene (C-1)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | FWHM of peak (β) radians | Particle size D (nm) |
|----------|------------------|------------------------|--------------------------|----------------------|
| 1. | 10.218 | (1 0 0) | 0.0060 | 23.735 |
| 2. | 10.840 | (0 0 2) | 0.0152 | 9.061 |
| 3. | 17.651 | (1 1 0) | 0.0093 | 14.921 |
| 4. | 20.621 | (1 1 2) | 0.0098 | 14.220 |
| 5. | 21.530 | (0 0 4) | 0.0034 | 41.049 |
| 6. | 30.888 | (3 0 0) | 0.0027 | 52.683 |
| 7. | 32.650 | (0 0 6) | 0.0044 | 32.470 |

According to Table 4, the range of particle size of prepared fullerene (C-1) were found to be 9.061-52.683 nm and average particle size is 26.877 nm.

Table 5 The Peak ID Report of Fullerene (C-1)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | Area (%) | Phase ID |
|----------|------------------|------------------------|----------|-----------------|
| 1. | 10.218 | (1 0 0) | 20.6 | C ₆₀ |
| 2. | 10.840 | (0 0 2) | 97.5 | C ₆₀ |
| 3. | 17.651 | (1 1 0) | 14.5 | C ₆₀ |
| 4. | 20.621 | (1 1 2) | 18.7 | C ₆₀ |
| 5. | 21.530 | (0 0 4) | 6.6 | C ₆₀ |
| 6. | 30.888 | (3 0 0) | 3.2 | C ₆₀ |
| 7. | 32.650 | (0 0 6) | 5.5 | C ₆₀ |

For C₆₀, the localized peaks at 2θ = 10.218°, 10.840°, 17.651°, 20.621°, 21.530°, 30.888° and 32.650° that referred to plane reflections of (100), (002), (110), (112), (004), (300) and (006), respectively. According to Table 5, phase ID of prepared C-1 was confirmed as C₆₀ and should be fullerene.

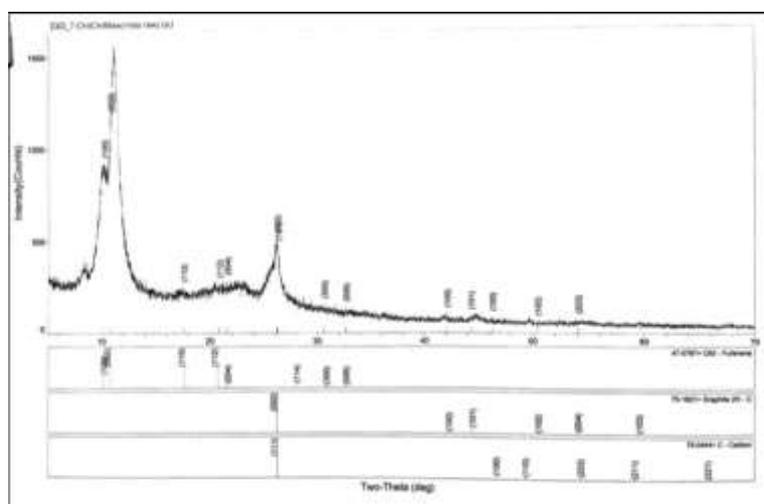


Figure 4 XRD diffraction pattern of fullerene (C-2)

Table 6 The Results from XRD Diffractogram of Fullerene (C-2)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | FWHM of peak (β) radians | Particle size D (nm) |
|----------|---------------------------|------------------------|----------------------------------|----------------------|
| 1. | 10.220 | (1 0 0) | 0.0122 | 29.025 |
| 2. | 10.841 | (0 0 2) | 0.0116 | 18.162 |
| 3. | 17.550 | (1 1 0) | 0.0071 | 19.542 |
| 4. | 20.831 | (1 1 2) | 0.0114 | 12.054 |
| 5. | 30.638 | (3 0 0) | 0.0066 | 21.539 |
| 6. | 32.668 | (0 0 6) | 0.0040 | 35.721 |

According to Figure 4 and Table 6, the range of particle size of prepared fullerene (C-2) were found to be 12.054-35.721 nm and average particle size is 27.829 nm.

Table 7 The Peak ID Report of Fullerene (C-2)

| Peak No | Bragg angle (2θ) | Miller indices (h k l) | Area (%) | Phase ID |
|---------|---------------------------|------------------------|----------|-----------------|
| 1. | 10.220 | (1 0 0) | 100.0 | C ₆₀ |
| 2. | 10.841 | (0 0 2) | 88.1 | C ₆₀ |
| 3. | 17.550 | (1 1 0) | 5.9 | C ₆₀ |
| 4. | 20.831 | (1 1 2) | 10.6 | C ₆₀ |
| 5. | 30.638 | (3 0 0) | 4.0 | C ₆₀ |
| 6. | 32.668 | (0 0 6) | 2.3 | C ₆₀ |

For C₆₀, the localized peaks at $2\theta = 10.220^\circ$, 10.841° , 17.550° , 20.831° , 30.638° and 32.668° that referred to plane reflections of (100), (002), (110), (112), (300) and (006), respectively. According to Table 7, prepared C-2 was confirmed as C₆₀ and should be fullerene.

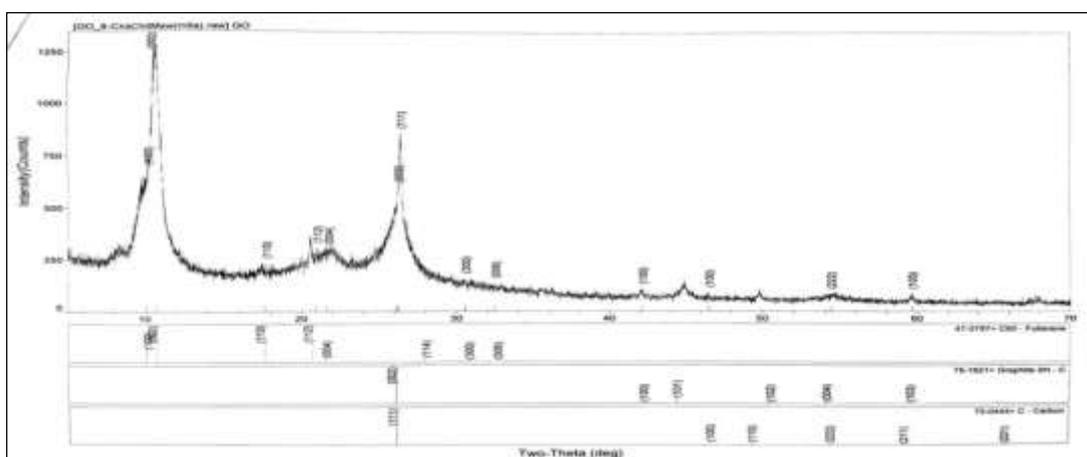
**Figure 5 XRD diffraction pattern of fullerene (C-3)**

Table 8 The Results from XRD Diffractogram of Fullerene (C-3)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | FWHM of peak (β) radians | Particle size D (nm) |
|----------|------------------|------------------------|--------------------------|----------------------|
| 1. | 10.150 | (1 0 0) | 0.0167 | 8.242 |
| 2. | 10.750 | (0 0 2) | 0.0095 | 14.496 |
| 3. | 17.655 | (1 1 0) | 0.0054 | 25.694 |
| 4. | 20.906 | (1 1 2) | 0.0027 | 51.638 |
| 5. | 21.632 | (0 0 4) | 0.0131 | 10.656 |
| 6. | 30.533 | (3 0 0) | 0.0038 | 37.402 |
| 7. | 32.470 | (0 0 6) | 0.0063 | 22.668 |

According to Figure 5 and Table 8, the range of particle size of prepared fullerene (C-3) were found to be 8.242-51.638 nm and average particle size is 24.399 nm.

Table 9 The Peak ID Report of Fullerene (C-3)

| Peak No | Bragg angle (2θ) | Miller indices (h k l) | Area (%) | Phase ID |
|---------|------------------|------------------------|----------|-----------------|
| 1. | 10.150 | (1 0 0) | 51.4 | C ₆₀ |
| 2. | 10.750 | (0 0 2) | 100.0 | C ₆₀ |
| 3. | 17.655 | (1 1 0) | 3.8 | C ₆₀ |
| 4. | 20.906 | (1 1 2) | 2.2 | C ₆₀ |
| 5. | 21.632 | (0 0 4) | 9.5 | C ₆₀ |
| 6. | 30.533 | (3 0 0) | 1.8 | C ₆₀ |
| 7. | 32.470 | (0 0 6) | 3.0 | C ₆₀ |

For C₆₀, the localized peaks at 2θ = 10.150°, 10.750°, 17.655°, 20.906°, 21.632°, 30.533° and 32.470° that referred to plane reflections of (100), (002), (110), (112), (004), (300) and (006), respectively. According to Table 9, the phase purity of prepared C-3 was confirmed as C₆₀ and should be fullerene.

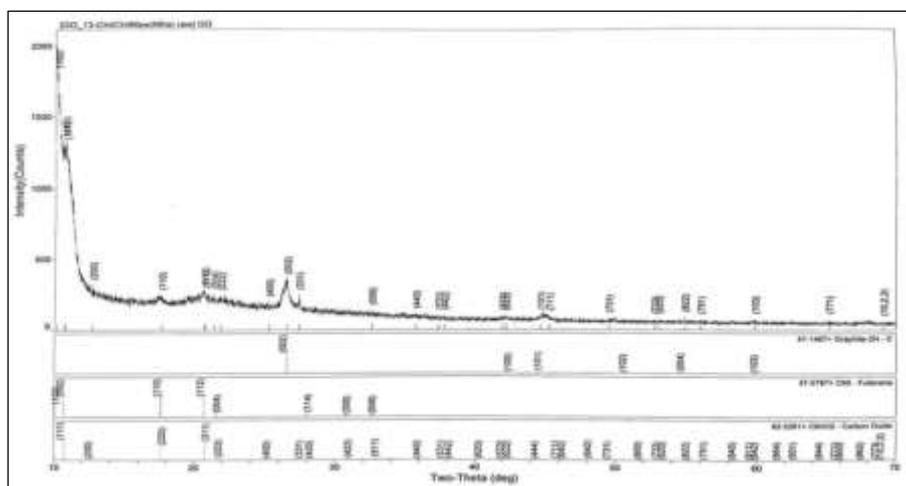


Figure 6 XRD diffraction pattern of fullerene (C-4)

Table 10 The Results from XRD Diffractogram of Fullerene (C-4)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | FWHM of peak (β) radians | Particle size D (nm) |
|----------|---------------------------|------------------------|----------------------------------|----------------------|
| 1 | 10.180 | 1 0 0 | 0.0065 | 21.206 |
| 2 | 10.730 | 0 0 2 | 0.0099 | 13.910 |
| 5 | 17.606 | 1 1 0 | 0.0078 | 17.788 |
| 6 | 20.640 | 1 1 2 | 0.0086 | 16.205 |
| 8 | 21.332 | 0 0 4 | 0.0069 | 20.220 |
| 9 | 32.570 | 0 0 6 | 0.0068 | 21.007 |

According to Table 10, the range of particle size of prepared fullerene (C-4) were found to be 13.910-21.206 nm and average particle size is 18.389 nm.

Table 11 The Peak ID Report of Fullerene (C-4)

| Peak No. | Bragg angle (2θ) | Miller indices (h k l) | Area (%) | Phase ID |
|----------|---------------------------|------------------------|----------|-----------------|
| 1 | 10.180 | 1 0 0 | 65.7 | C ₆₀ |
| 2 | 10.730 | 0 0 2 | 99.8 | C ₆₀ |
| 3 | 17.606 | 1 1 0 | 5.2 | C ₆₀ |
| 4 | 20.640 | 1 1 2 | 7.4 | C ₆₀ |
| 5 | 21.332 | 0 0 4 | 4.1 | C ₆₀ |
| 6 | 32.570 | 0 0 6 | 2.6 | C ₆₀ |

For C₆₀, the localized peaks at $2\theta = 10.180^\circ$, 10.730° , 17.606° , 20.640° , 21.332° , and 32.570° that referred to plane reflections of (100), (002), (110), (112), (004) and (006), respectively. According to Table 11, prepared C-4 was confirmed as C₆₀ and should be fullerene. Average particle size for four prepared fullerenes (C-1 to C-4) are listed in Table 12. From these data the average particle size of prepared fullerene were nano.

Table 12 Average Particle Size for Fullerene (C-1 to C-4)

| No. | Fullerene | Average Particle Size (nm) |
|-----|-----------|----------------------------|
| 1. | C-1 | 26.877 |
| 2. | C-2 | 27.829 |
| 3. | C-3 | 24.399 |
| 4. | C-4 | 18.389 |

Thermal Stabilities of Prepared Fullerene by TG -DTA

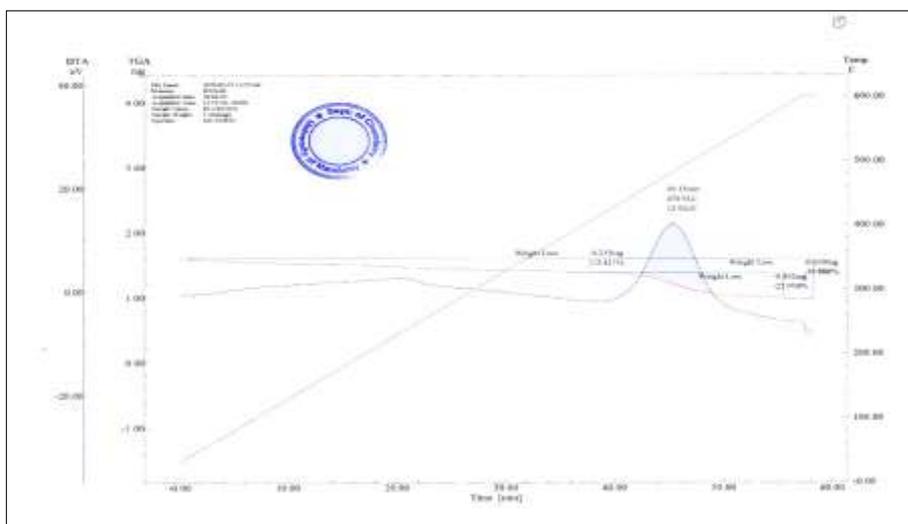


Figure 7 TG-DTA thermogram of fullerene C-1

Table 13 TG-DTA Analysis of Fullerene C-1

| No. | Temperature (°C) | Weight loss (%) | Type of peak | Remark |
|-----|------------------|-----------------|--------------|--|
| 1. | 229.42 | 13.421 | exothermic | Due to the loss of moisture and impurity |
| 2. | 479.91 | 39.888 | exothermic | Break down of some bonds and degradation occur |

According to Figure 7 and Table 13, the maximum degradation was found to be 479.91°C and the weight loss is 39.888 %. The thermal analysis of C-1 shows basically two mass loss steps (TG) with corresponding thermal events in the DTA curves. The first steps up to 229.42 °C show mass losses 13.421 % due to the physically adsorbed water on the material and impurity, probably occurred during storage. The second mass loss step (479.91 °C) may be the break down of some bonds and degradation of carbon skeleton.

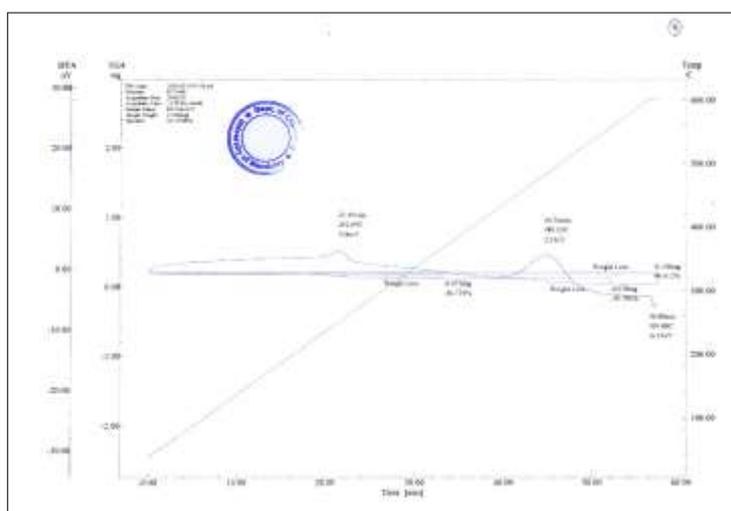
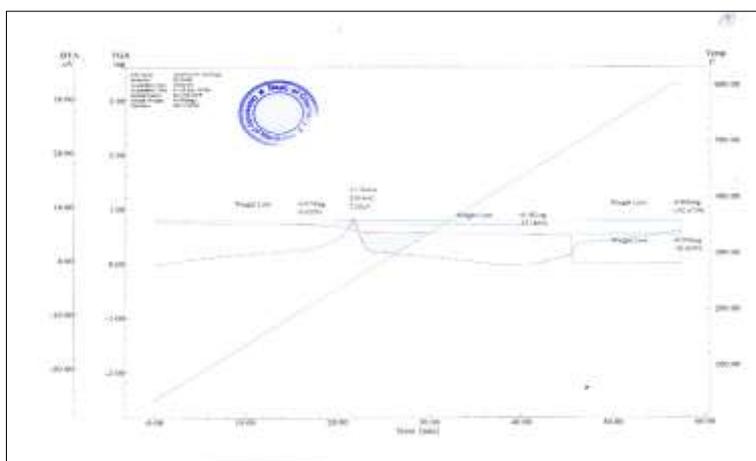


Figure 8 TG-DTA thermogram of fullerene C-2

Table 14 TG-DTA Data Analysis of Fullerene C-2

| No. | Temperature (°C) | Weight loss (%) | Type of peak | Remark |
|-----|------------------|-----------------|--------------|--|
| 1. | 252.09 | 36.735 | exothermic | due to the loss of moisture and impurity |
| 2. | 484.05 | 39.796 | exothermic | break down some bonds and degradation occurs |
| 3. | 599.80 | 80.612 | exothermic | break down some bonds and degradation occurs |

According to Table 14, the maximum degradation was found to be 599.80 °C and the weight loss is 80.612 %. The thermal analysis of C-2 (Figure 8) shows three mass loss steps (TG) with corresponding thermal events in the DTA curves. The first steps up to 252.09 °C show mass losses 36.735 % due to the physically adsorbed water on the material and impurity. The second mass loss step (484.05 °C) and the third mass loss step (599.80 °C) can be assigned to the break down of some bonds and degradation of carbon skeleton.

**Figure 9 TG-DTA thermogram of fullerene C-3****Table 15 TG-DTA Analysis of Fullerene C-3**

| No. | Temperature (°C) | Weight loss (%) | Type of peak | Remark |
|-----|------------------|-----------------|--------------|--|
| 1. | 253.44 | 23.185 | exothermic | Due to the loss of moisture and degradation occur in some extent |
| 2. | 300.20 | 100.00 | exothermic | Complete degradation occur |

According to Table 15, the maximum degradation was found to be 300.20 °C and the weight loss is 100.00 %. The thermal analysis of C-3 (Figure 9) shows two mass loss steps (TG) with corresponding thermal events in the DTA curves. The first step up to 253.44 °C show mass losses 23.185 % due to the physically adsorbed water on the material and impurity. The second step at 300.20 °C can be assigned to occur complete degradation (100% mass loss).

Morphology of Prepared Fullerenes by SEM

The morphology of graphite, prepared C-1 and C-3 were analysed by SEM microscopy (Figures 10).

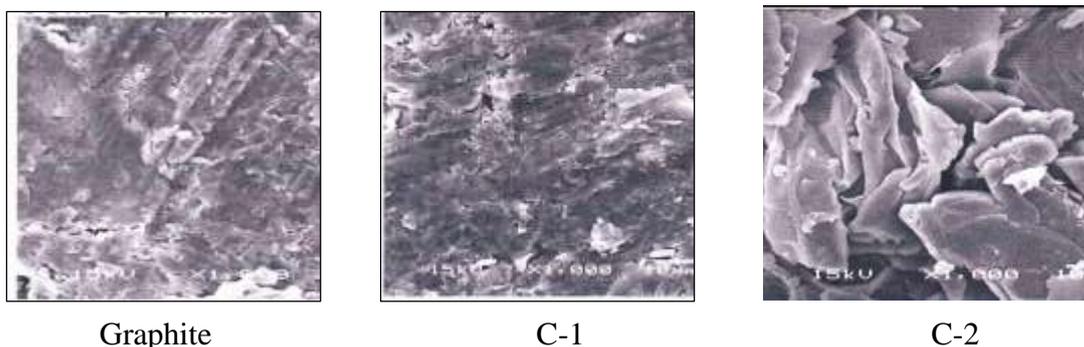


Figure 10 SEM image of graphite and prepared fullerenes (C-1) (C-2)

According to SEM microscopy, in graphite, graphene sheets are packaged with a distance between sheets. The SEM image of C-2 shows disorganization of material and a greater distance between sheets that indicates there was an expansion and change of graphite due to the aspect of crumpled and exfoliated.

Conclusion

In this research, the preparation of fullerene (C-1 to C-4) was carried out from graphite by the changing amount of NaNO_3 , H_3PO_4 , KMnO_4 and H_2SO_4 with various time intervals such as stirring times and sonication times, respectively. The yield percent of fullerene were found to be 73.02 % for C-1, 76.08 % for C-2, 74.52 % for C-3 and 88.40 % for C-4. The crystalline size and crystal nature of graphite and fullerene were investigated by XRD spectra. From the XRD result, the particle size of graphite was found to be 152.76-855.98 nm. The average particle size of graphite was found 490.47 nm. The average particle size of prepared fullerene were found to be 26.877 nm in C-1, 27.829 nm in C-2, 24.399 nm in C-3 and 18.389 nm in C-4 respectively. From the XRD data, the prepared fullerene C-1 to C-4 were confirmed according to 2θ value and ID phase. Furthermore, the thermal stability of fullerene was determined using thermo-gravimetric analysis (TG-DTA). From the TGA data, the fullerene started to degrade at 229.42 °C (13.421%) in C-1, 252.09 °C (36.735 %) in C-2 and 253 °C (23.185 %) in C-3. The maximum degradations were found to be 479.91 °C (39.888 %) in C-1, 599.80 °C (80.612 %) in C-2 and 300.20 °C, (100.0 %) in C-3. Among them, C-3 was completely decomposed at 300.2 °C. Finally, the surface morphology of graphite and prepared fullerene were analyzed by SEM microscopy. According to SEM microscopy, the morphology of graphite was found as packaged sheets. The SEM image of C-2 shows disorganization of graphite.

Acknowledgements

The authors would like to thank the Department of Higher Education (Lower Myanmar), Ministry of Education, Yangon, Myanmar, for allowing us to carry out this research programme. Thanks are also extended to the Myanmar Academy of Arts and Science and Professor Dr Ni Ni Aung, Head of Department of Chemistry, Meiktila University for allowing to carry out this research programme.

References

- Anthony, J.W., Bideaux, R. A., Bladh, K.W and Nichols, M.C. (eds). (1990). "Graphite"., Hand Book of Mineralogy. I (Elements, Sulfides, Sulfosalts). Chantilly, VA; US: Mineralogical Society of America.
- Deitz, T.G., Duncan, M.A., Powers, D.E. and Smalley, R.E. (1981). "Laser Production of Supersonic Metal Cluster Beams", *J. Chem. Phys.*, vol. 74, pp. 6500-6511.
- Fears, R, Kenneth, D., Krug, H., Aebi, K, Stamm, H. and Anklam, E. (2011). "Impact of Engineered Nanomaterials on Health Consideration for Benefit-Risk Assessment Joint Research Centre Corporate Activities", Publications Office of the European Union.
- Hahens W.I., Oomen A.G., Dejong W.H. and Cassee, F.R. (2007). What Do We Know about the Kinetic Properties of Nanoparticles in the Body? *Regulatory Toxicology and Pharmacology*, vol. 49, pp.217- 229.
- Hawkins, J.M., Meyor, A., Lewis, L.A., Loren, S. and Hollander, P.J. (1991). "Crystal Structure of Osmylated C₆₀: Confirmation of the Soccer Ball Framework", *Science*, vol. 252, pp. 312-313.
- Kratschmer, W., Lamb, L., Fostiopoulos, K. and Hoffman, D.R. (1990). "Solid C₆₀- a New Form of Carbon", *Nature*, vol. 347, pp.354-358.
- Kronholm, D. and Hummelen, J.C. (2007). "Fullerene-based n-type Semiconductors in Organic Electronic", *Mater. Metters*, vol. 2, pp.16-19.
- Roco, M.C., (2004)." Nanoscale Science and Eengineering. Unifying and Transforming Tools", *AIChE J.* vol.50, pp.890-897.
- Tagmatarchis, N. and Shin Ohara, H. (2001). "Fullerenes in Medicinal Chemistry and their Biological Application", *Mini-Rew. Med Chem-1*, pp.339-348.
- Xiao, L., Takada, H., Maeda, K., Haramoto, M. and Miwa, N. (2005). "Antioxidant Effects of Water-soluble Fullerene Derivatives against Ultraviolet Ray or Peroxylipid through their Action of Scavenging the Reactive Oxygen". *Species in Human Skin Keratinocytes, Biomed, Pharmacotherapy*, vol. 59, pp.351- 358.