Concrete with Enhanced Ductility using Structural Microfibers

Shane M. Palmquist
Western Kentucky University
Shane.Palmquist@wku.edu

Ramyasree Annam
Western Kentucky University
Ramyasree.Annam340@topper.wku.edu

Abstract

Concrete is one of the most widely used construction materials in the world and is typically composed of portland cement; water; aggregates such as sand, gravel or crushed stone; and admixtures. Unlike steel, concrete is a quassi brittle material. For design purposes, the tensile strength of concrete is assumed to be negligible since it is relatively weak in tension. Reinforcing steel is added to concrete for this purpose because steel is relatively strong in tension and has greater ductility. In recent years, materials like fiber reinforced cementitious composites have been expored and developed. Many types of fibers with varying sizes have been examined in concrete in hopes of developing more ductile cementitious materials than traditional concrete. The components of these fiber reinforced cementitious materials are very similar to traditional concrete, except no coarse aggregates are used and air entrainment is not necessary. And like traditional concrete, fiber reinforced cementitious materials are made to be cost effective. Numerous large scale potential applications exist including: buildings, bridges, airports, culverts, dams, and projects involving repair or rehabilitation work.

The focus of this paper is to present the results of a fiber reinforced cementitious composite that has been developed over time based on work found in the literature with modifications based on experimentation of mix designs using high performance polyvinyl acetate (PVA) microfibers. Cube test specimens were cast and tested in compression and indirect tension. In addition, a large chamber scanning electron microscope examined fiber crack bridging of post failed cube specimens that were loaded in indirect tension (split cube tests). Results show test specimens of concrete reinforced with PVA microfibers exhibit a decrease in compressive strength but a significant increase in indirect tensile strength and have more ductility than specimens not containing the fibers, such as more traditional types of concrete.

Introduction

In the last few decades, growing interest has developed in using fibers in ready-mixed concrete, precast concrete and shotcrete. Fibers made from steel, plastic, glass, wood and other materials have been used in concrete. Fibers are typically added to concrete mixes in low volume dosages often at rates less than 1.0% by volume for the purposes of reducing

ISBN 978-1-60643-379-9

plastic shrinkage cracking [1]. However, fibers do not significantly affect the free shrinkage of concrete, but given high enough dosages, fibers can increase the resistance to cracking and decrease the size of the crack widths [2].

Generally, fiber reinforced concrete is grouped into two classes: thin sheet products and bulk structure products. Fiber fraction volumes further determine subclassifications and uses for each class, with low-volume fiber fractions (<1%) primarily serving to resist plastic shrinkage and high-volume fiber fractions (2>-10%) serving to provide additional or secondary reinforcement to main reinforcing steel. High volumes (up to 20% steel fibers) have been demonstrated to significantly improve all strength properties. Fiber reinforced concrete has become synonymous with various steel fiber reinforcements. However with the addition of steel fibers, there is an increase in weight. Perhaps, concrete in the form of a cementitious composite could be developed which utilize nonferrous type structural fibers. This materials would have the goal of capitalizing on the additional strength of fibers, while providing a significantly lighter composite material. One such possibility is the use of synthetic polymer fibers.

Synthetic fibers are the result of research and development in the petrochemical and textile industries. Synthetic fibers that have been used in portland cement concrete include: acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene. One problem associated with synthetic fibers is the ability of the fibers to disperse and distribute evenly in the composite, providing a good compatible and continuous to bond between the fibers and the cementitious paste matrix. Polypropylene fibers are commonly used as a fiber in portland cement concrete since the fibers are chemically inert, hydrophobic, and lightweight. Fibers of this type are generally added at a rate of 0.1% by volume of concrete. Polypropylene fibers can reduce plastic shrinkage cracking and help reduce spalling of concrete.

For many years, researchers have attempted to produce concrete that is more ductile in behavior [3,4]. See Figure 1. In most cases, ductile concrete has been achieved using fiber reinforcement[1]. Concrete with synthetic polymer fibers such polypropylene microfibers is the result of this development effort. This material has demonstrated impressive ductile behavior. Bending can be achieved with a high level of inelastic deformation resulting from the development of numerous microcracks with limited crack widths. This is in sharp contrast to traditional concrete, where a single point of failure (crack with a large crack width) develops from excessive bending.

Research and development by Dr. Victor C. Li of the University of Michigan, Ann Arbor has produced a type of concrete using these types of fibers which has greater ductility than traditional types of concrete [5,6]. This material has been used in a number of projects worldwide and is proposed for many other projects [7]. The largest use of this material to date has been as a 5 mm thick topcoat on the Mihara Bridge in Hokkaido, Japan. Domestically, the Michigan Department of Transportation (MDOT) has used this material for various surface patches and as a flex joint (replacement for steel expansion joint) on a bridge deck crossing over I-94 in Ypsilanti, Michigan.

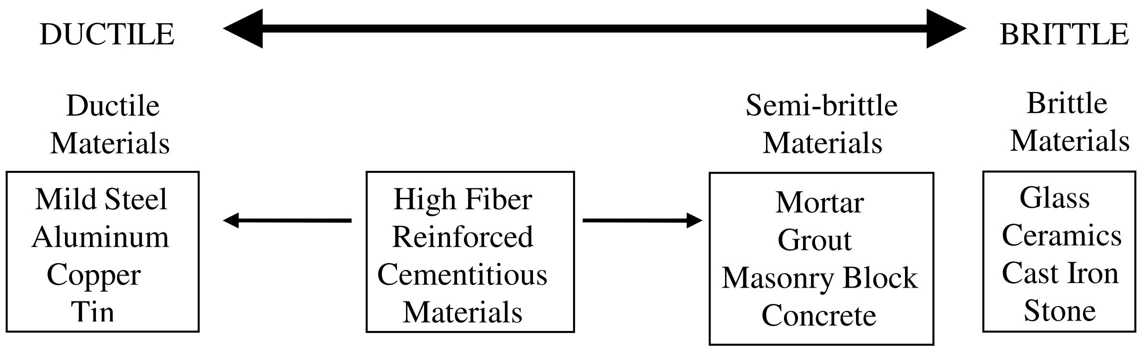

Figure 1: Range of Ductile to Brittle Behavior of Materials

The research herein is to examine a type of concrete reinforced with PVA microfibers and compare it to the same concrete without fibers. The project was conducted in two phases. The first phase was to cast cubes to compare compressive and indirect tensile strengths of the concrete with and without PVA microfibers. The second phase was to use a large chamber scanning electron microscope to examine PVA microfiber bridging across concrete cracks of cube specimens that were loaded to failure in indirect tension (split cube tests).

Polyvinyl Alcohol Microfibers

Polyvinyl alcohol (PVA) microfibers at the molecular level consist of repeated structural units of $-[-CH_2-CH(OH)-]_n-$. Usage of PVA microfibers as a reinforcement material leads to many benefits. Apart from being economical, the PVA microfiber reinforcement improves the quality of concrete by making it fatigue and corrosion resistant. Polyvinyl acetate is the starting material in the manufacturing of polyvinyl alcohol (PVA).

PVA is hydrolyzed by treating it with an alcoholic solution in the presence of an aqueous acid or alkali. OH groups present in PVA are capable of forming hydrogen bonds between the fibers and the cement matrix. The resulting surface bonding helps in bridging across cracks. The tensile strength of PVA fibers is significantly higher than mild steel rebar used in reinforced concrete, which also contributes towards improved bridging performance when cracks develop and propagate. See Figure 2.

Comparative Concrete Batch Designs

Two batches of concrete were cast. The first batch was the baseline concrete containing no microfibers. The secong batch of concrete was reinforced with PVA microfibers. The microfibers were added at a volume fraction of 2.2%. The microfibers had a length of 8 mm. See Figure 3. All other components were measured and kept identical to the baseline concrete for comparative purposes. Portland cement type III was used since it is finer than type I. Super plasticizer (Glenium 3000 NS) was used to increase the workability of concrete. Glenium 3000 NS is a high-range water reducing admixture. The resulting mix was prepared using a water to cement ratio of 0.59. The details of the mix design employed to establish baseline concrete cubes are summarized in Table 1, where the amount of each component is given in kilograms per cubic meter of concrete cast.

Figure 1: KURALON® Ultra High Performance Nycon PVA Microfibers

Figure 3: Incorporation of PVA Microfibers in Concrete

Experimental Tests

A total of two batches of concrete were cast, one batch being the baseline concrete and the other batch being the concrete reinforced with PVA microfibers. All other mix proportions were the same between the two concrete batches. Each batch produced a total of 48 specimens, which were 50 x 50 x 50 mm cubes in size. From each batch, 24 cubes were tested in compression, and the other 24 cubes were tested in indirect tension (split cube test).

Table 1. Concrete Mix Proportions

Component	Amount (kg/m^3)
Portland cement (type III)	605.5
Fine aggregate (sand)	484.4
Fly ash (type C)	726.6
Water	353.2
Super plasticizer (Glenium 3000 NS)	8.6

For the baseline concrete, four cubes each were tested in compression at 1, 3, 7, 14, 21, and 28 days to determine the compressive strength gain as a function of curing time. The same was performed for the concrete reinforced with PVA microfibers. Also for the baseline concrete, four cubes each were tested in indirect tension (split cube test) at 1, 3, 7, 14, 21, and 28 days to determine the indirect tensile strength gain as a function of curing time. This was also done for the concrete reinforced with PVA microfibers. See Figure 4.

Indirect tensile strength (split cube tensile strength) was calculated using the following formula,

$$\sigma_{sp} = 0.519\, P / S^2$$

where P is the failure load in Newtons and S is the length of the side in millimeters of the concrete cube [8].

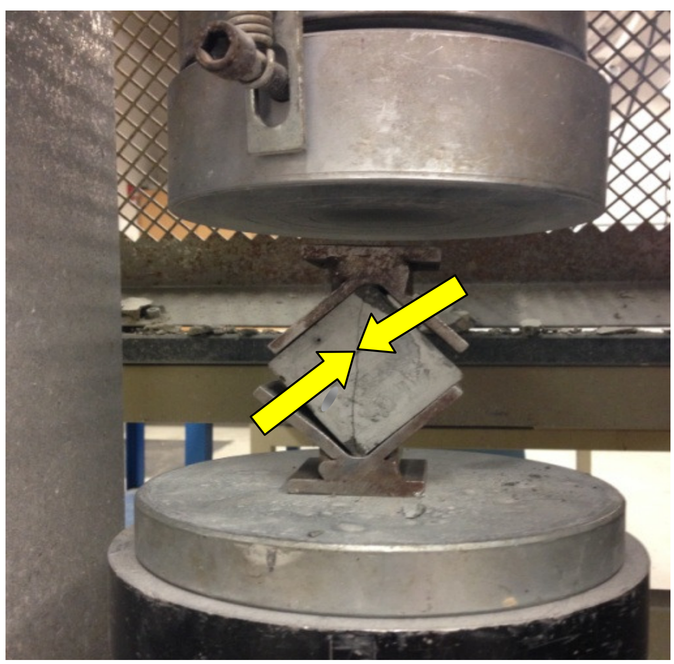

Figure 4: Vertical Crack in Split Tensile Strength Test Cube

A large chamber scanning electron microscope (LC-SEM) was used for imaging of the cubes with fibers. These cubes were first tested in indirect tension (split cube test) and then examined using the LC-SEM.   A vertical crack formed during the test and the PVA microfibers were observed to be bridging across the cracks. To better demonstrate the bridging of the microfibers across the crack, imaging was done using an LC-SEM.

LC-SEM is a scanning electron microscope used for high resolution imaging. This instrument accommodates large samples without the need of cutting them into small pieces causing damage to the specimens. The magnification power of the instrument is up to 300,000x. The images generated by the instrument have a resolution greater than 10 nm. This instrument helped to better understand the nature of fiber bridging that occured across the concrete cracks that developed. Figure 5 shows the LC-SEM available at the WKU NOVA Center, only two LC-SEMs exist in the world.

Figure 5: Large Chamber Scanning Electron Microscope at WKU NOVA Center

Testing Results

A graph was plotted showing the average compressive strength and the age of the concrete cubes with and without fibers. See Figure 6. The concrete batch without fibers is referred to as the baseline concrete, while the other batch is referred to as the concrete with PVA fibers. Not including the day 1 results, the fiber reinforced concrete cubes exhibited on average 26.7% less compressive strength than the cubes without fibers. The fibers in the composite cause the formation of voids in the presence of filling material (sand). This results in the improper packing of the concrete there by decreasing the compressive strength of the specimen [9].

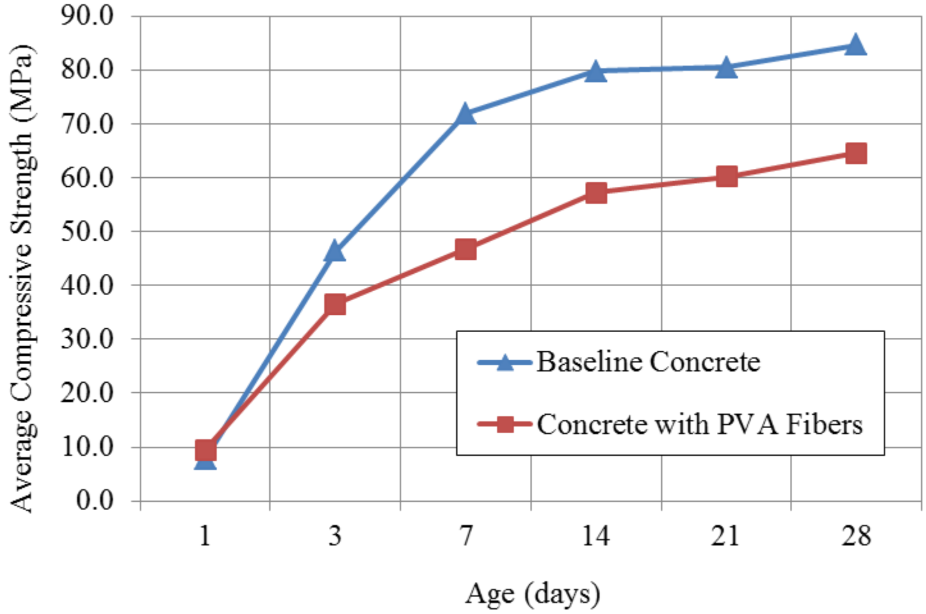

Figure 6: Compressive Strength at Various Ages

A graph was plotted showing the average indirect tensile strength (split cube tensile strength) and the age of the concrete cubes with and without fibers. See Figure 7. The fiber reinforced concrete cubes exhibited on average 57.4% more indirect tensile strength than the cubes without fibers.

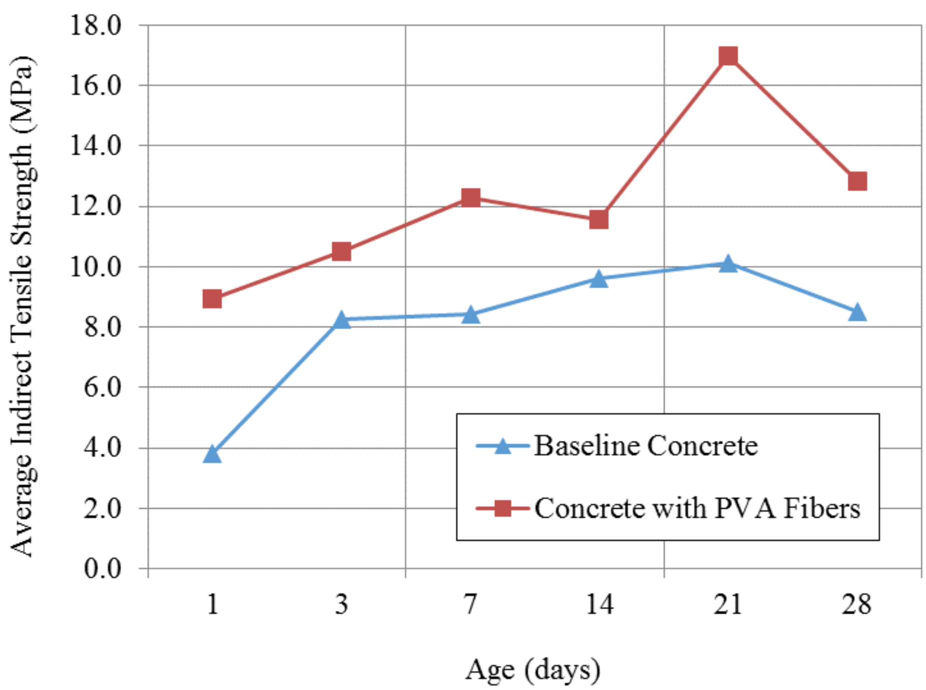

Figure 2: Indirect Tensile Strength at Various Ages

SEM images of concrete cubes tested for split tensile strength were collected. Figure 8 shows the fibers bridging across the crack. It also shows that the fibers are pulled between the crack and they are under stress. When a crack is formed in PVA fiber reinforced concrete, the fibers act as bridges or stiching between the cracks which helps to prevent or limit the formation of macrocracks. These fibers undergo tension as they are pulled in between the cracks. PVA microfiber pullout from the cementitious matrix was not observed.

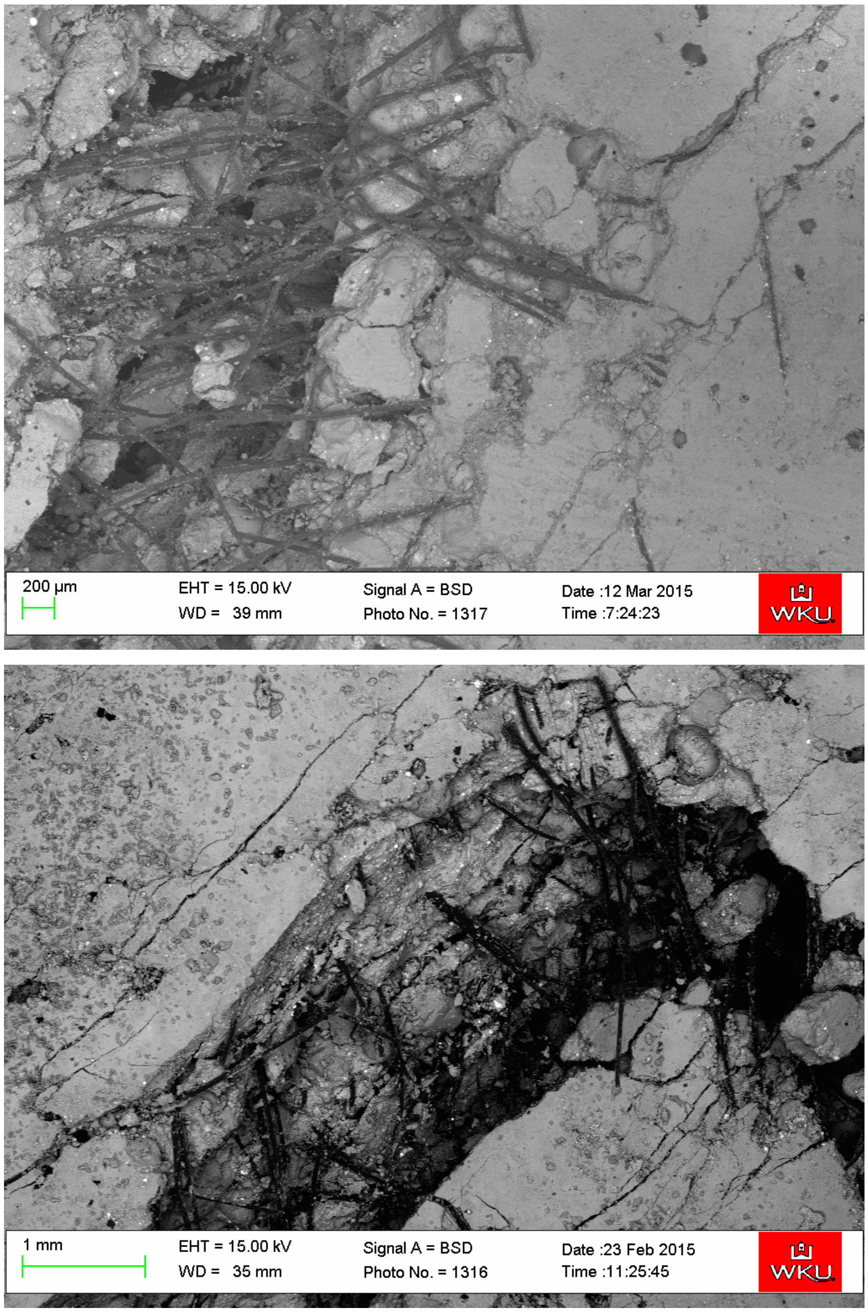

Figure 8: SEM Images of Fibers Bridging Cracks in Concrete

Summary and Conclusion

The effect of PVA fiber loading of 2.2% by volume on the mechanical properties of concrete was examined. Compressive strength and indirect tensile strength testing was done for both baseline concrete cubes and PVA microfiber-reinforced concrete cubes. When compressive strength was examined as a function of curing time, the concrete cubes with PVA microfiber reinforcement exhibited 26.7% less compressive strength than the baseline concrete cubes which contained no fibers. Whereas when indirect tensile strength was examined as a function of curing time, the concrete cubes with PVA microfiber reinforcement exhibited 57.4% more indirect tensile strength than the baseline concrete cubes. Increase in the indirect tensile strength shows that the concrete has gained ductility.

SEM imaging of the samples was done to observe fiber bridging across the concrete cracks. Based on the images collected, all cracks observed were shown to have PVA microfibers bridging across the crack widths. PVA microfiber pullout from the cementitious matrix was not observed.

Special Thanks

The authors would like to thank the Foundation at Western Kentucky University for financial support of this project. The authors would also like to thank Dr. Cate Webb, associate dean of Ogden College at Western Kentucky University for her support throughout this project as well as to Dalton Hankins and Kyle Parks, two civil engineering seniors, for assisting in fabricating and testing of the cubes in the materials laboratory. Finally, the authors are greatful to Dr. Edward Kintzel for assistance with the large chamber scanning electron microsope.

References

[1] Kosmatka, S. H., Kerkhoff, B., and Panarese, W. C. (2006). *Design and Control of Concrete Mixtures.* (14th ed.). Skokie, IL: Portland Cement Association.

[2] Shah, S. P., Weiss, W. J., and Yang, W. (1998). Shrinkage Cracking – Can it be prevented? *Concrete International,* American Concrete Institute, Farmington Hills, MI, 51-55.

[3] Li, V., (1997). Engineered Cementitious Composites (ECC) – Tailored Composites through Micromechanical Modeleing, Advanced Civil Engineering Materials Research Laborotary, University of Michigan. Release of abstract appeared in "*Fiber Reinforced Concrete: Present and the Future*". Canadian Society of Civil Engineers.

[4] Wang, S., and Li, V. (2005) Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composites: Material Design and Performances, RILEM Workshop on High Performance Fiber Reinforced Cementitious Composites (HPFRCD) in Structural Applications, Honolulu, HI, 65-73.

[5] Li, V., On Engineered Cementitious Composites (ECC) – A Review of the Material and its Applications. *Journal of Advanced Concrete Technology*, 1(3), 215-230.
[6] ASTM, (2004) *Annual book of standards, concrete and aggregates*. (Vol. 4.02). Philadelphia, PA.
[7] ECC Technology Network, http://www.engineeredcomposites.com/Applications/mihara_bridge.html.
[8] Badagha, G. D., and Modhera, D. C. (2013). Studies on harden properties of mortar using carbon fibers. *International Journal of Advancements in Research and Technology*. 2, 249-252.
[9] Nuruddin, F.M., Khan,U.S., Shafiq, N., and Ayub, T. (2014) Strength Development of High-Strength Ductile Concrete Incorporating Metakaolin and PVA Fibers. *The Scientific World Journal*. 1-11.

Biographies

SHANE M. PALMQUIST is an associate professor of structural engineering in the Department of Engineering at Western Kentucky University and is the Ritter Professor of civil engineering. Dr. Palmquist is also the coordinator of the civil engineering program, and is a licensed professional engineer in Kentucky. Prior to becoming a faculty member at WKU, Dr. Palmquist was a bridge engineer for Lichtenstein Consulting Engineers in Natick, Massachusetts. He earned his B.S. degree in civil engineering from the University of New Hampshire, 1995; an M.S. in structural engineering from the University of Rhode Island, 1996; and his Ph.D. in structures/materials engineering from Tufts University, 2003. His research and technical interests include: project-based engineering education, cable supported structures, and cementitious materials with enhanced properties using fibers. Dr. Palmquist may be reached at Shane.Palmquist@wku.edu.

RAMYASREE ANNAM just completed her master of science degree from the Department of Chemistry at Western Kentucky University. Her thesis research focused on studying the mechanical properties of PVA fiber reinforced concerete with Raman spectroscopy analysis. Ms. Annam may be reached at Ramyasree.Annam340@topper.wku.edu.