Enhancing the Mechanical Properties of Concrete Using Pitch-Based Carbon Fibers

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Abstract—**This paper tested the mechanical properties of adding pitch-based carbon to the concrete mix, and investigated the thermal behavior and electrical conductivity. The experiment made use of recycled pitch-based carbon fibers with length ranging from 7 mm to 15 mm. The recycled carbon fibers were added to the concrete mix in proportions of 0.5%, 1%, 1.5% and 2% of the concrete weight. The American Society for Testing and Materials (ASTM) procedure was used in the mix design and testing of the concrete specimens. The use of short carbon fibers in the concrete mix led to improvement in its tensile and compressive strengths. The thermal conductivity of the concrete composite decreases with increasing fibers. The use of fibers creates void in the concrete leading to a higher thermal resistivity of the concrete composite. The carbon fiber reinforced concrete creates a higher electrical conductivity.**

Index Terms—**Carbon fibers, recycled, mechanical properties, ASTM.**

I. Introduction

A. Background and Problem Statement

Concrete is the most widely used construction material. It is popular due to its compressive strength, resistance to fire, durability, relatively low cost, sustainability, and its can be formed to any shape. However, plain concrete is weak under tension. Plain concrete is brittle and has a low strain and tensile strength capacities. In order to overcome these weaknesses, concrete is often reinforced. Apart from the common steel reinforcement, there is a growing trend in fiber reinforcement of concrete (FRC). Fiber reinforced concrete is a "concrete incorporating relatively short, discrete, discontinuous fibers" [1]. Although the fibers added to fiber reinforced concrete (FRC) are not meant to increase strength, tests have shown that some moderate strength increases occur. Fibers in FRC are mainly used to modify the post-cracking behavior of concrete. The fibers act as "bridges" between cracked surfaces to improve the post-cracking ductility of concrete. FRC has seen an increase in applications in recent years. More than 76 million cubic meters of concrete was produced for use in surface slabs, precast concrete members, and other structural forms. There are many different types of fibers that are used in reinforcing concrete. The most common ones are cellulose, carbon, steel, polymers, asbestos and glass. The fibers are chosen base on their costs, geometry, effectiveness and physical properties. For instance, the use of carbon fiber has previously been limited in FRC due to its high cost. The decrease in cost and higher demands for better structures with high functional properties has seen the use of carbon fiber rise. These fibers are normally 5 mm in length and are used as admixture in concrete [2]. These short fibers are less expensive when compared to long or continuous fibers. Additionally, it is possible to use the short fibers directly in a concrete mix. Composites made from carbon fibers exhibit attractive tensile and flexural properties, low shrinkage, high specific heat, low thermal conductivity, high electrical conductivity, high corrosion resistance and weak thermoelectric behavior [2] .These improvements have seen carbon fiber concrete composites widely used in structural elements. However, short carbon fibers have been found to form weak bonds with concrete matrix. Thus, continuous fibers are widely used in reinforcing concrete. The bond between the carbon fiber and the matrix can be improved using techniques such as surface treatment by heating, using ozone, or using hot NaOH solution. The surface treatment using Silane and Ozone help to improve the bond by enhancing the wettability of the surfaces of the fibers. The properties of the concrete composite vary with the volume of fiber fraction. High fiber volume increases the air void content in the composite. High air voids has negative effects on concrete properties such as compressive strength. Additionally, high fiber content can reduce the workability of the concrete. The cost of the concrete also increases with addition of carbon fibers. Therefore, the fiber fraction should be maintained at the minimum desirable content. In practice, the fiber content of between 0.2% and 1% by volume is commonly used. The fiber content is varied with the size of the aggregate. Large aggregates require higher fiber content. However, the flexural strength of a concrete composite decreases with the size of the aggregates. Carbon fibers are more effective if they are distributed evenly in the concrete mix. This dispersion is achieved through the admixture such as silica fume. The silica content is also used to enhance workability. Latex, although not effective in enhancing dispersion, can also be added as an admixture to enhance workability, acid resistance, flexural toughness, flexural strength, frost resistance and impact resistance. Although carbon fibers improve properties of concrete such as tensile and flexible strength, increasing their size reduces the flexural and tensile strength. Carbon fibers can improve the temperature and strain sensing ability, thermoelectric activity, and insulation properties of concrete. Carbon fibers addition increases the air voids leading to lower thermal conductivity of concrete. The electrical conductivity increases with addition of carbon fibers irrespective of the increase in voids. The varying properties of carbon fiber reinforced concrete with

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different volume of carbon make it challenging to use the composites in structural work. In order to apply the carbon fibers in reinforcing concrete, it is important to investigate how different properties of concrete are affect by the different volumes of carbon fibers. This paper will hence investigate how the properties of concrete such as compression strength, tension strength and point compression are influenced by varying the amount of fibers in the concrete mix.

B. Objectives

The properties of fiber reinforced concrete are affected by the types of fibers, the size of fibers, and the volume of fibers. Some of the properties such as compressive strength, tensile strength, electrical and thermal conductivity, and workability are affected by the nature, size and volume of fibers used. The objective of this study was to investigate how the properties of carbon fiber reinforced concrete are affected by the volume. The research was thus guided by the following specific objectives:

- To compare the mechanical properties of carbon fiber reinforced concrete and that of plain concrete.
- To investigate how the 28-day compressive strength of carbon fiber reinforced concrete varies with the volume of fibers.
- To investigate how the 28-day tensile strength of carbon fiber reinforced concrete varies with the volume of fibers.
- To investigate the thermal conductivity of carbon fiber reinforced concrete.
- To investigate the electrical conductivity of carbon fiber reinforced concrete.

C. Project Approach

The project approach taken in this study is experimental. In this study, a sample carbon fiber reinforced concrete cylinder is designed and tested for its compressive and tensile strengths. The volume of carbon fiber in concrete is varied from 0% (for control cylinder) to 2% and the cylinders tested for their mechanical properties. The concrete batches were designed a tested following the American Society for Testing and Materials (ASTM) procedure. The testing results were analyzed using Excel program. The performance of carbon fiber reinforced concrete was compared against the control composite. Additionally, the mechanical properties of the concrete composites were analyzed with increasing volume of fibers.

II. State of Literature

A. Introduction

According to Chung [3], concrete is strong under compression but brittle when under tension or flexure. However, the addition of fibers has been identified as one of the ways that can be used to improve the tensile properties of concrete. It should be noted that fibers are not used as a replacement for the common steel reinforcement in structural concrete. While reinforcement steels are used to improve the load-bearing capacity of concrete, fibers are used mainly to control cracking. The use of fiber reinforced concrete has been increasing steadily over the past few years. There are many different types of fibers that are in an application today. The most common types of fibers are steel, carbon, polymer, glass, asbestos, and cellulose [1]. The use of different fibers is based on their effectiveness, costs, and geometry. One of the fibers that have seen the recent increase in usage is carbon fiber. Previous research have shown that addition of 2% carbon fibers can improve the tensile properties of concrete by approximately 100% [5].

B. Types of Fibers

The most commonly used types of fibers are steel, glass, carbon, polymer and cellulose. This section outlines the characteristics of the fibers.

Steel fibers: these fibers are made through the cutting of steel wires, sheets or from molten steel. The steel fibers are made in such a way that they are either deformed along their lengths or with hooks at the ends in order to improve their bonding in the cement. These fibers have a problem with rusting when they are exposed to the surface of the concrete matrix. However, when they concealed in the concrete mass, they are highly durable

Glass fibers: these fibers are produced from molten glass in the form of filaments. The glass fibers are either chopped or stranded. Some of the glasses cannot be used in concrete because they can easily be attacked by an alkaline environment. Glass fibers are mainly used in architectural thin sheets.

Asbestos fibers: According to Mindess et al. [1], the natural occurring asbestos fibers have been applied in construction since in the early twentieth century. The ease of mixing asbestos fibers with concrete led to its early application. The concrete composite reinforced with asbestos is highly resistant to abrasion and corrosion. However, the main disadvantage of the asbestos fibers is that they are carcinogenic. Due to the health risks of asbestos, they have been replaced by the use of other fibers.

Synthetic fibers: these synthetic fibers have low elastic modulus than concrete. They are widely applied to reduce the plastic shrinkage of concrete. According to Mindess *et al.* [1], they also improve the toughness of concrete.

Natural organic fibers: the natural organic fibers include elephant grass, sisal, jute, and sugarcane bagasse. These fibers have low modulus but tend to deteriorate in the alkaline environment if they are not well treated. The fibers are widely used in developing countries to produce low-cost housing units.

Cellulose fibers: the fibers have been found to have higher elastic modulus than the natural fibers. The fibers also have higher tensile strength than the natural fibers. When processed well, they can be used to replace asbestos fibers.

Carbon fibers: these fibers have high modulus and high tensile strength. Although these fibers have been found to be very effective in improving the properties of concrete, their application has been limited by their high costs.

C. Fiber-Matrix Bonding

The bonding between fibers and concrete matrix influences the properties of concrete. The formation of bonds in fiber reinforced concrete depends on the chemical reactions that occur between the concrete composite and the fibers. This bond also change with time as the concrete ages.

The concrete is more porous in the regions around the fibers than in other regions. In some regions, the cement matrix may be unable to penetrate between fiber filaments leading to the creation of voids. In such cases, the fiber filaments that are located in the middle of others do not bond well with concrete. When the fiber reinforced concrete is well designed, the primary mode of failure of such composite is the pullout of the fibers. The fiber pullout requires more energy than breaking the fibers. In steel fibers, the forces include friction, adhesion, and interlock of the fibers. In glass fibers, chemical reactions help to improve the bonds. The bond in natural fibers is due to mechanical interlock of fibers. Deforming the fibers at their edges or along their length helps to improve the mechanical interlock in the matrix.

D. Mechanical Properties of Fiber Reinforced Concrete

The main use of fibers is to increase the interlock of the matrix to reduce cracking. The fibers help in improving the post-cracking behavior of concrete. The addition of fibers does not improve the strength of concrete. The cracking pre-cracking behavior of concrete is not affected by the addition of fibers. However, when fibers are added in the concrete composite, the post-cracking behavior is improved. The fibers help to improve toughness and post-cracking load bearing capacity of concrete. The fibers may improve the post-cracking strength through transferring of weight across the cracks. The toughness of fiber reinforced concrete is improved through the gradual deformation and pull out of fibers. However, in the case of long fibers, they may fail through yielding at high strains.

Strength: Although fibers are not primarily added to improve the strength of concrete composites, they have been shown to increase the compressive strength slightly. The fibers do not improve the tensile strength of concrete significantly either. The addition of fibers up to about 1.5% has been shown to improve the tensile strength of concrete by about 30%. The adjustment of the water-content ratio is much more effective in improving the strength of concrete than the addition of fibers. It is worth noting that the fibers do not have any significant effects on the torsional and shear strength of concrete composites. The use of fibers does not affect the elastic modulus of concrete significantly.

Toughness: Fibers are very effective in improving the toughness of concrete. They do so by acting as bridges in the cracking planes. They join two planes together hence improving the load-bearing capacity of the concrete element in its post-cracking phase. The fibers have high stiffness and strength, and if the concrete-fiber bonds are sufficient, the can be effective at limiting the width of the cracks in concrete. Thus, the use of fibers helps to improve post-cracking ductility or toughness. The toughness of concrete can be obtained by calculating the area under the stress-strain curve. Toughness is the measure of the amount of energy absorbed by the fiber reinforced concrete.

Although the use of fibers does not improve the strength of concrete, they help in improving the post-cracking properties. The improvement in the properties of concrete is more noticeable after the cracking. The increase in fiber content in the concrete composite increases the toughness of concrete. Fibers with high bonding capacity have a higher ability to improve the toughness of concrete. In order to improve toughness, fibers that either deformed at the edges or along the length are usually used in concrete.

In order to improve the properties of FRC, the fibers should be designed to fail by pullout rather than breaking. The effectiveness of the fiber used in concrete is thus influenced by its stiffness as well as its geometry. The geometry of a fiber is defined by its edge characteristics, its surface deformations, and its length. There is a lot of research going on to improve the geometry of fibers.

The toughness of concrete can best be measured during flexural loading of a specimen. The fiber reinforced concrete is designed to withstand flexure. The methods for determining the flexural properties of concrete are outlined in the ASTM C 1018-97 guidelines [6]. The method recommends that 4x4x14 inches specimen should be loaded using the three-point loading method. The load should be recorded against the deflection at the middle point of the specimen.

Impact resistance: The ability of plain concrete to resist impact is very minimal. However, this ability can be greatly improved through the addition of fibers. Carbon fibers and steel fibers are known to be very effective in improving the impact resistance of concrete. Although synthetic fibers also improve the peak loads during impact, they are not very effective at improving the impact resistance of concrete. There are no well-developed and standardized tests for measuring impact resistance of materials. However, methods such Pendulum or Charpy test and explosive loading tests can be used. When the load is applied at a high rate, the majority of the fibers fail by breaking rather than pulling out. The tendency to break rather than pullout is influenced by the weak geometry of the fibers currently in use. A lot of research is ongoing in order to improve the geometrical properties of fibers. The addition of fibers has also been found to improve the ability of concrete to resist abrasion.

Fatigue: Fiber reinforced concrete has been shown to improve the fatigue resistance of concrete. The fatigue resistance is improved through the ability of fibers to bridge together planes of concrete after cracking.

Creep and shrinkage: The addition of fibers has not been found to improve the creep or shrinkage properties of concrete. However, fibers tend to reduce the width of cracks when concrete crack during shrinkage. Fibers have been shown to improve the plastic shrinkage of concrete. Some fibers such as polypropylene are used primarily to reduce plastic shrinkage.

Durability: In order to improve the durability of concrete, it should be made impermeable and dense. Studies have shown that the addition of fibers in well-designed concrete mixes can help reduce the permeability of concrete. However, the decrease is permeability due to the addition of fibers has not been found to be significant in improving the life of concrete.

Whereas steel fibers may rust and corrode, synthetic fibers do not rust. In order to improve the durability of steel fibers, they should be concealed within the concrete matrix. Stainless steel may be used in areas that are highly susceptible to corrosion. However, the use of stainless steel leads to extra costs in construction. Glass fibers are also susceptible to attacks in alkaline environments. Natural fibers such as sisal and jute are also likely to be attacked by bacteria and fungus.

Thermal behavior of FRC: The thermal properties of concrete are important in the design of energy-efficient structures. Materials with low conductivity prevent loss of heat energy to the surrounding. The thermal properties of concrete are influenced by its constituents. The amount of cement, air sand, and aggregates affect the thermal conductivity of concrete. The thermal conductivity of cement depends on the amount of water used in the mix design. A porous cement matrix has low thermal conductivity properties. Although some fibers such as carbon and steel are good conductors of heat, their addition in the concrete lead to the creation of voids. The voids in concrete lead to reduction in their thermal conductivity ability.

Electrical behavior of FRC: Plain concrete has low electrical conductivity ability. The electrical conductivity of concrete is influenced by the presence of electrical conductors in its matrix. The aggregate present in concrete can be replaced by materials that are conductive such as steel and carbon to improve its conductivity [4]. The use of fibers can help to improve the conductivity of concrete while maintaining it desirable structural properties. A conductive concrete has wide applications in de-icing of highways, driveways, airports runways, and parking garages.

E. Application of FRC

The use of fibers has been found to improve the overall properties of concrete. When the FRC is well designed, it has wide applications in the construction of structures. However, it is advisable that before using fibers, one should evaluate other methods of improving properties of concrete such as reducing the water content and improving workmanship. Steel fibers can be used in the design of airports runways and pavements. The use of fibers helps to reduce the thickness of pavements and cracking. The toughness of FRC makes it ideal for use in industrial floors. The use of FRC helps to reduce damages on the floor due to impact and abrasion. The FRC is also used in lining tunnels. Some fibers such as polypropylene are used to reduce plastic shrinkage of concrete.

III. METHODOLOGY

A. Introduction

This section outlines the methodological procedures that were used to investigate the properties of the fiber reinforced concrete (FRC) with pitch-based carbon fibers. The section outlines the selection of materials, the batching process, the curing process, the testing process, and the analysis process used in the research.

B. Materials

- Carbon fibers: the carbon fibers used in the experiment were recycled pitch-based fibers. They were made of various nominal lengths that ranged from 7 mm to 15mm.
- Fine aggregates: the fine aggregate was natural sand. FA was tested to obtain absorption, specific gravity, and finance modulus based on the procedures outlined in ASTM: C128-07, C1252-06 and C33-08 [7]-[9].
- Coarse aggregates: CA was tested to find the absorption, specific gravity, dry rodded unit weight, and the maximum size of aggregates based on the procedures outlined in ASTM: C33-08, C127-07, and C29-09 [7], [10], and [11].
- Portland cement type I.

C. Equipments

- Mixers: a concrete mixer with a flat beater was used.
- Trowels: they were used for spreading, leveling and smoothing molds.
- Scoop: used for scooping concrete into molds.
- Buckets: used for mixing and storage of water.
- Balance: used for measuring weight of materials during batching.
- Cylinder molds: used for creating molds.
- Marking pen: used for labeling molds as per fiber contents.
- Equipment specified in the slump test.

Fig. 1. A photo of the recycled carbon fibers used in the concrete mixes.

Fig. 2. A photo of the mixer used in the experiment.

A. Mixing Procedures

The concrete batches were made following ASTM procedure. The mixing procedures used in this experiment were separated in two ways. The first way is following the exact ASTM standards, and the second way was to follow the procedure but with dry mix of fine aggregate with carbon fibers. In both cases, a concrete mixer with a flat beater was used to mix the concrete. The following steps outline the procedure that was followed in the batching process.

- The fine and the coarse aggregate samples were weighed using the balance. The total amount of moisture in the aggregate was determined and subtracted in order to obtain the dry weight of the aggregates.
- Adjustments in batch weights were made in order to obtain the weight of aggregates.
- The weight of the quantities needed was calculated and obtained ready for the mix.
- The mixture was dampened before the mixing could be done.
- Carbon fibers were mixed with the fine aggregate.
- The coarse and the fine aggregates were added into the mixer.
- In order to prevent dust from escaping from the mixture, the mouth of the mixer was covered.
- The mixer was started and left to run for one minute in order to mix the coarse and the fine aggregates.
- Cement was then added and the mouth of the mixer covered to prevent dust from escaping. The mixer was started and left to run for one minute in order to mix cement with the aggregates. After the one minute, the mixer was stopped and water added.
- After the water was added, the mixer was started and left to run for three minutes. The concrete was allowed to rest for 3 minutes before the mixer was run for further 2 minutes. The 2-minutes rest was allowed in order to prevent false setting. The mouth of the mixer was covered during the rest to prevent evaporation of water.
- The concrete was then deposited from the mixer into a clean and dump container.
- The concrete was remixed using a trowel to prevent segregation. The trowel was wetted first before it was used. The mixing was done until concrete appeared uniform.
- Four 4 × 8 in. cylinder molds were prepared to receive concrete by first oiling their inner surfaces
- The four 4 × 8 in. cylinders concrete molds were made following the manner outlined by ASTM C 192-05 [12].
- The percentage composition of carbon fibers in the concrete was identified and each cylinder labeled accordingly as per the sharpie.

Fig. 3. A cylindrical concrete mold labeled according to its percentage carbon fiber composition.

- The specimens were left near the casting area in position on a grid level that is free from any form of disturbance. The specimens were then covered using plastic cover that was fitting slightly.
- On the following day, the cylinders were stripped, marked and placed in the water tank.

D. Curing Procedure

The cylinders were stripped from the molds and immersed in a water tank. The specimens were left for 7 and 28 days before testing was done.

E. Mechanical Testing

The cylinders were tested for compression and tensile strength tests. The tests were done following ASTM standards. For each type of test, specimens from the plain, 0.5%, 1%, 1.5, and 2% batches were tested. The area under the load-deflection curve in the compression can be used to calculate the toughness of the specimen for further investigation.

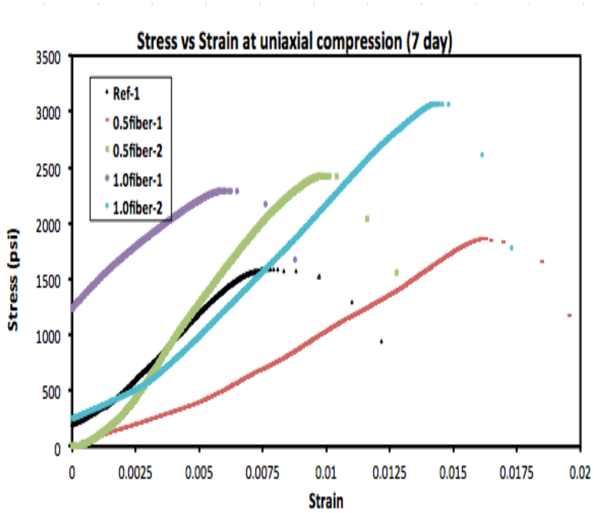

Fig. 4. Stress against strain at uniaxial compression at 7 days.

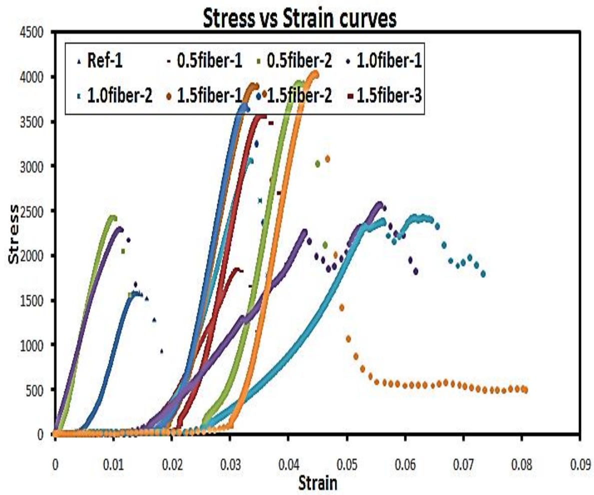

Fig. 5. Stress against strain at uniaxial compression at 28 days.

IV. Results and Findings

The mechanical properties of concrete improved with the addition of the pitch-based carbon fibers in the concrete. The mechanical properties investigated were the compressive strength and the tensile strength of the specimens.

A. Compressive Strength

The results show that the use of carbon fibers increased the compressive strength of concrete composites. The compressive strength of carbon fiber reinforced concrete was highest at the intermediate fiber content. The highest compressive strength was found at the optimum fiber content of 1% of concrete weight. The Fig. 4 and 5 below illustrate the stress-strain curve after 7 days and 28 days respectively that was obtained with the addition of fibers to the concrete mixes.

B. Point Compression

The figure 6 below illustrates the peak compression of concrete after 28 days with the addition of pitch-based carbon fibers.

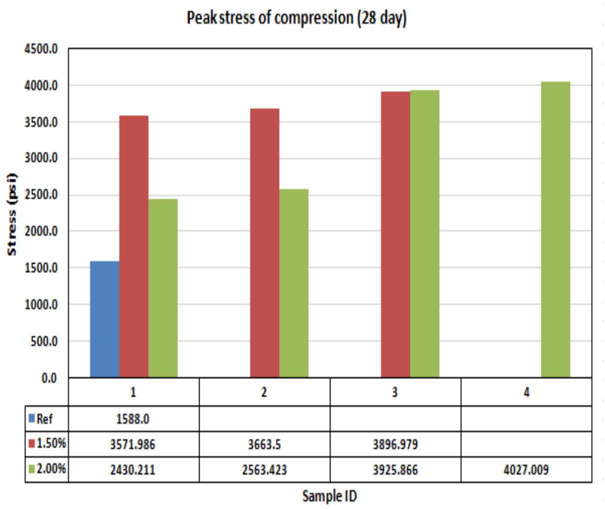

Fig. 6. The peak compression of concrete at 28 days.

C. Tensile Strength

The figure 7 below shows the peak stress of split tension after 28 days of concrete samples with addition of pitch-based carbon fibers.

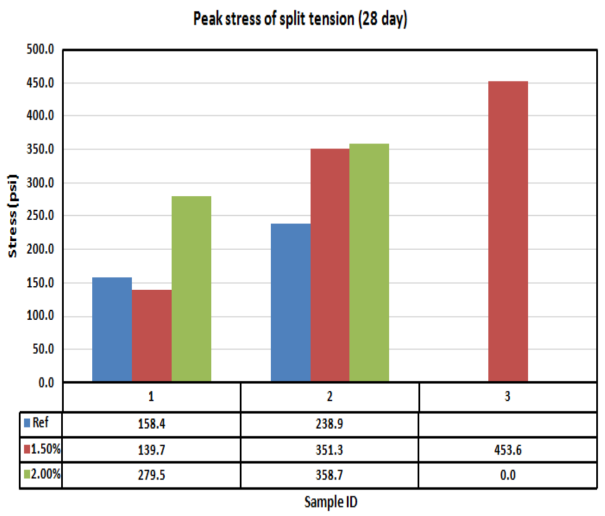

Fig. 7. The peak stress of split tension after 28 days.

D. Microscopy

The surface of the concrete cylinder was scanned using a camera after the compression test was performed. The scanning was done in order to observe the nature of fractures formed on the surface of the cylinders with varying the volume of carbon fibers. The surface of the concrete indicated that some of the carbon fibers had pulled out after the force was applied. The pullout fibers pattern indicated that the fibers were evenly distributed in the concrete composite. The size of the fractures decreased with the increasing volume of fibers.

Fig. 8. A photo of a fractured concrete cylinder showing exposed fibers.

V. Conclusion

This paper tested the mechanical properties of adding pitch-based carbon to the concrete mix, and investigated the thermal behavior and electrical conductivity. The experiment made use of pitch-based recycled carbon fibers with length ranging from 7 mm to 15 mm. The recycled carbon fibers were added to the concrete mix in proportions of 0.5%, 1%, 1.5% and 2% of the concrete weight. The use of short carbon fibers in fiber reinforced concrete led to improvement in its tensile and compressive strengths. The thermal conductivity of the concrete composite decreases with increasing fibers. The use of fibers creates a void in the concrete leading to a higher thermal resistivity of the resulting concrete composite. The carbon fiber reinforced concrete increases electrical conductivity.

The carbon fibers cannot be used to replace the steel reinforcement bars. However, the carbon fiber reinforced concrete has wide applications in which it can be used together with steel bars to improve the performance of structural elements. When used together with steel bars, the carbon fibers are more effective. They are effective in bridging the cracks and hence prevent excessive spalling and exposure of steel reinforcement bars. The carbon fibers also help in improving the bonding between the concrete matrix and the steel bars. Carbon fibers can be used to resist seismic forces in areas prone to earthquakes. In some cases, the carbon fibers have been applied to improve the shear behavior of columns and beams. However, the use of carbon fibers has been limited in application in structural elements. The design of concrete put more emphasis on toughness and strength. The design codes need to be revised in order to incorporate the use of fibers in structural design.

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