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SUSTAINABLE BUILDING SYSTEMS – ALTERNATIVE CONSTRUCTION MATERIALS

by
ELIE ANTOINE AWWAD

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Approved by

Dr. Mounir Mabsout, Professor Civil and Environmental Engineering	co-Advisor
Dr. Bilal Hamad, Professor Civil and Environmental Engineering	co-Advisor
Dr. Ghassan Chehab, Assistant Professor Civil and Environmental Engineering	Member of committee
Dr. Mohamad Talal Farran, Professor Poultry Nutrition and Production Engineering	Member of committee
Dr. Hisham Basha, Professor Civil and Environmental Engineering, Beirut Arab University	Member of committee
Dr. Adnan Masri, Professor Civil and Environmental Engineering, Beirut Arab University	Member of committee

Date of dissertation defense: August 19, 2011

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Concrete production contributes enormously to natural resources depletion due to the large amounts of aggregates consumed during the production process, in addition to cement production which contributes to the greenhouse gas production affecting global warming and climate change. Concrete production needs to become more sustainable by saving on natural resources while being durable. Research on synthetic and industrial fibers used in concrete mixes is available in the literature. Most of the previous research on natural fibers applications has been conducted on fiber-reinforced cement rather than fiber-reinforced concrete. Researchers have investigated the use of natural fibers in cement mortars for their applications mostly in thin sections such as pipes and others. Due to their wide availability and simplicity in production, industrial hemp fibers are gaining much interest for their inclusion in construction materials.

The objective of the research is to produce a sustainable green concrete. The new found material incorporates industrial hemp fibers that are classified as agricultural, cheap, and waste material. The use of hemp fibers results in a ductile and flexible concrete material in addition to the reduction in coarse aggregates.

The research is divided into three main phases. The trial phase covered the potential concrete mixes compatible with the fibers. Different natural and synthetic fibers were investigated. One unique concrete mix was adopted and only industrial hemp fibers were selected for further investigation. The first phase included twelve mixes and a large set of performance tests in order to optimize the best hemp fiber-reinforced concrete mix. A statistical analysis and analytical linear models were also included. In the second and last phase, two hemp mixes were selected in addition to a control mix, for further investigation in structural beam elements. Three modes of failures were investigated flexure, shear, and bond failure modes. Eighteen steel reinforced-beams were prepared and tested.

The various test results indicated the possibility of including hemp fibers in concrete mixes while saving on the coarse aggregate quantity, and producing a ductile and energy absorbent material.

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To My Beloved Family

CHAPTER 1
INTRODUCTION

1.1. Introduction

The traditional trend for the production of any material focuses on its properties, shape, strength, and other "practical" concerns, while ignoring the raw material availability and the potential for its depletion. Nowadays, the trend is shifting toward finding production technologies which encapsulate saving on natural resources. Sustainable development can be described as the process for communities to develop and prosper without depleting natural resources which provide all types of raw materials for the development of societies. For instance, trees, fossil fuel, and rock aggregates are the natural resources for paper, energy, and concrete production, respectively. Thus, if such raw materials are continuously exploited and depleted, future generations will encounter shortage problems and will suffer from the scarcity of certain much-needed raw materials. Consequently, sustainable development aims at saving natural resources without negatively affecting the standard of living of societies and communities. The interest in sustainability is therefore gaining wide acceptance worldwide and is not only related to engineering and construction areas, but it also deals with all other aspects that affect global warming, climate change, and depletion of natural resources.

In the construction industry, concrete is one of the main components that contribute to the natural resources depletion due to the large amounts of aggregates consumed during the production process, in addition to cement production, which contributes to the greenhouse gas production affecting global warming and climate change, for every one ton of cement production results in about one ton of CO_2 emission. The current trend is to produce a durable concrete of high performance, instead of a very high strength concrete which is less durable. Durable concrete is expected to last longer and to be able to absorb more dynamic and impact loads, without being deteriorated.

1.2. Sustainable or "Green" Concrete

The cement industry is one of two primary producers of carbon dioxide. Cement manufacture contributes to greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is heated, producing lime and carbon dioxide, and also indirectly through the use of energy, particularly if the energy is sourced from fossil fuels. The cement industry produces 5% of global human-made CO_2 emissions, of which 50% is from the chemical process, and 40% from burning fuel.

Both concrete and asphalt are the primary contributors to what is known as the urban heat island effect. Using light-colored concrete has proven effective in reflecting up to 50% more light than asphalt and reducing ambient temperature. A low albedo value (the fraction of incident radiation, as light, that is reflected by a surface or body), characteristic of black asphalt, absorbs a large percentage of solar heat and contributes to the warming of cities. By paving with light colored concrete, in addition to replacing asphalt with light-colored concrete, communities can lower their average temperature. The potential of energy saving within an area is significant; with lower temperatures due a lower thermal conductivity, the demand for air conditioning decreases, thus saving vast amounts of energy. Similarly is the case with heating load requirements in cold areas.

For a concrete material to satisfy some sustainability aspects in addition to an adequate structural performance, it may be a concrete that can be produced while saving on natural resources, in addition to having low thermal conductivity properties. Thus, such newly investigated “green” concrete would have some positive and desirable effect on natural aggregate and energy resources depletion.

In the current research, the natural fibers are incorporated in concrete mixes and expected to satisfy the above mentioned sustainability criteria, by reducing the coarse aggregate quantities, and reducing the thermal conductivity of concrete material.

1.3. Fibers in Cement and Concrete

The problem with brittle building materials, such as plain concrete in tension, has been considered since ancient times; many solutions and methods were tried in order to allow for a ductile behavior after the first crack. Some early examples of these reinforcement techniques were such as clay reinforced with straw, and masonry mortar reinforced with animal hair. The reason for using fibers in both cement and concrete composites is to enhance the properties of the weak, brittle, and crack-prone cementitious matrix.

The first sophisticated product made with fiber-reinforced technique was asbestos-cement. Asbestos-cement was used in thin layers in the pipe industry. These pipes were made by the asbestos fibers mixed with cement slurry, water, and sometimes with fine silica, sand or other additives. Asbestos-cement, manufactured using different processes, has been widely used in sheeting, roofing, cladding panels, and in pipes since 1900s. However, since 1970, the asbestos use has declined because of the associated hazard to human health due to breathing asbestos fibers. Consequently, research efforts were directed toward finding alternative fibers for engineering applications in thin-section form. Some of these newer cement composites are glass, carbon, and others.

Similar to the use of industrial fibers in concrete, “natural” fibers have also been tried in concrete and cement mixes, such as bamboo, jute, coconut, sisal, and hemp fibers. Natural fibers advantages, as their name hints, are characterized by their natural existence without the need of any industrial effort. They are also prone to have a positive effect on the farming industry by increasing the demand for such plantation in the fields which produce natural fibers. However, it is commonly known that natural fibers may degrade over long term and result in strength loss when used in concrete. Further, the use of any type of fibers, whether natural or industrial has drawbacks. For instance, the use of glass fibers in concrete is affected by the alkaline environment of concrete. Another example is with the use of steel fibers that may be affected by the carbonation of concrete, in case it occurs, and consequently the steel fibers may degrade and result in loss of strength.

The trend toward using environmentally friendly building material is gaining more acceptance with the problem of natural resources depletion such as aggregates used in concrete mixes. The search for natural fibers that can be feasible for production and viable for performance is currently of high interest for many researchers in the field. Hemp fibers are increasingly used to strengthen cement, and in other composite materials for many construction and manufacturing applications. One example is Hempcrete used as a construction material containing hemp hurds, especially in France. Hempcrete is a mixture of hemp hurds and lime (possibly including sand, pozzolan or cement) used as a material for construction and insulation. It is marketed under names like Hemcrete and Isochanvre (Allin 2005). The hemcrete is known to have good thermal insulation properties.

1.4. Research Objectives

Based on the literature review, the majority of research work focused on the incorporation of natural fibers in mostly cement/mortar mixes more than in concrete or in reinforced concrete mixes, and without consideration of any reduction in aggregates quantities. In the current research program, the use of industrial hemp fibers is primarily investigated, in addition to other natural fibers such as banana and palm, and other synthetic fibers tested for comparison purposes. The core of the research focuses therefore on the hemp fibers, and the possibility of introducing in reinforced concrete buildings or other structural applications.

In the current research, the “structural” performance of concrete using natural fibers which has not been seriously investigated in previous work will be the main subject of the thesis. Further, and since the target is to reach a sustainable material, two sustainable features were investigated. It was therefore decided to try to incorporate different agricultural fibers, considered as waste product, in concrete mixes, in lieu of synthetic or industrial fibers. Besides, the possibility of reducing the coarse aggregate quantity in order to save on natural resource depletion is also investigated.

1.5. Research Significance and Local Context

The effect of natural admixtures usage on concrete mixes can be interpreted mainly by the reduction of aggregates quantities. Consequently, producing similar or even better mixes with less aggregate quantities, results in a sustainable concrete that could be feasible and viable for structural applications. Moreover, once agricultural crops are found to be satisfactory in concrete mixes, the local harvesting of such crops would be recommended. Especially, industrial hemp would be an advantageous substitute to its sister "illegal" drug plant. Growing hemp requires no pesticides, replenishes the soil with nutrients and nitrogen, controls erosion of the top soil, and produces a lot of oxygen. The demand for the industrial hemp fibers for concrete production would be a major incentive to Lebanese farmers to grow this plant as a substitute to the illegal one, and benefit from the social impact on the habitat level of living.

A preliminary feasibility study was set by the United Nations Development Program (UNDP) and the Lebanese Ministry of Agriculture (MoA) project; it shows that the cost to produce industrial hemp is about $79 per dunum (1,000 square meters and non-irrigated lands) and the corresponding products value is about $192 which include seeds and stalks, raw material to produce respectively oil and fibers (MoA/UNDP Report, 2009). Therefore, the farming of industrial hemp appears to be a beneficiary business, and would be strongly supported if additionally the use of hemp fibers in concrete would prove to be satisfactory, resulting in demand increase and a prospering agricultural crop. Such a renewable agricultural crop would have multi-uses and an endless array of applications starting from oil production and its applications in food market and medicine, clothes production from fibers, insulation materials used in automobile and building application, paper production, textiles production, in addition to applications in concrete and many others.

In summary, the new material is to be produced using elements that are naturally available such as agricultural industrial hemp. The output may be considered to fit the criterion of sustainable building design since when compared with regular cement or concrete mixes, it is expected to: (i) improve physical characteristics and structural performance thus requiring less material; (ii) reduce material and energy resources depletion; (iii) provide a material with better thermal property and therefore increase energy efficiency; and (iv) contribute to sustainable living through improving livelihood conditions of rural and farming communities by using agricultural or recycled waste products.

1.6. Research Methodology

The research is mainly divided into three phases: trial, first, and second phases. The preliminary or trial phase was launched to investigate the possibility and the performance of different agricultural fibers like banana, palm, and hemp fibers in concrete mixes, in addition to synthetic fibers like steel and polypropylene as well as control mixes without fibers for comparison purposes. Many mixes were tried in order to determine an optimal concrete mix that is best suited with the fibers addition. Once the optimal mix was determined, different mixes were prepared and tested where two variables were investigated: the fibers type and volume fraction, and the coarse aggregate reduction. All other properties were kept constant throughout the trial phase. The fibers volume fraction was varied between 0.5, 0.75, and 1.0% associated with coarse aggregate reduction of 10, 20, and 30% by volume of concrete. The monitoring tests were the compression tests on cubes of 7 cm size, and the flexural tests on beams of 5 x 5 x 20 cm size. In all seventeen mixes were prepared and cast: control, steel, polypropylene, banana, palm, and hemp mixes. The trial phase mixes included 68 beams and 66 cubes, tested at 10 and 28 days.

At the end of the trial phase and based on the results, it was decided to go further with the hemp fibers only, and perform a full-scale tests series. Therefore, in phase 1, the hemp fibers were adopted in addition to polypropylene fibers again for comparison purposes. In this phase, all samples sizes were prepared according to standard specifications for different tests. Two variables were adopted while other factors were kept constant: the hemp fibers volume fraction and the coarse aggregate reduction. As in the trial phase, the fibers volume fraction was varied between 0.5, 0.75, and 1.0% associated with coarse aggregate reduction of 10, 20, and 30% by volume of concrete. A control mix with no fibers and no aggregate reduction was also included in the testing program. The tests performed included the compressive strength on standard cylinders (15 x 30 cm), flexure third-point load test on standard beams (15 x 15 x 53 cm), splitting tensile test on standard cylinders, and modulus of elasticity on standard cylinders. In addition, the following useful tests were conducted: slump tests of the fresh concrete mixes, density at hardened state, and a thermal conductivity test. Compression and flexure tests were performed at early and late concrete ages, whereas other tests were performed at only 28 days concrete age. All tests samples were prepared with 3 replicates for a better statistical representation. One-way and two-way ANOVA statistical analyses with 95% confidence level were also performed. In all twelve concrete mixes were prepared and cast: control, polypropylene, and hemp mixes. Consequently, a total of 180 cylinders, 72 beams, and 12 blocks were prepared, tested, and reported in the first phase. The first phase was ended by setting analytical linear models to predict the compressive strength, modulus of elasticity, and flexure tests results of the hemp-fiber concrete mixes, at 28 days concrete age, and based on correspondent control tests data.

Based on the phase 1 results, it was concluded that the hemp fibers had an acceptable performance in the concrete matrix, and it was decided to go further and monitor the performance of the new mix in structural elements such as simply supported reinforced concrete beams with typical steel reinforcement bars. Therefore, in the second phase, three main mixes were adopted, a control mix with no fibers and no coarse aggregate reduction, a 0.75% hemp mix with 20% coarse aggregate reduction, and a 1.0% hemp mix with 20% coarse reduction. The simply supported beam size was 20 x 30 x 200 cm, tested under a third-point load testing set. Three beams reinforcement types were also prepared: flexure, shear, and bond. Flexure beams were designed and prepared according to the American Concrete Institute (ACI) design requirements for flexure and shear reinforcement details. The shear beams were under-reinforced with respect to shear reinforcement in order to reach a shear failure. The bond beams were prepared with minimum splice requirement in order to make sure to ensure a bond failure. Two identical beams were prepared for every concrete mix and reinforcement beam type. Therefore, six beams (2 flexure, 2 shear, and 2 bond samples) were prepared for each of the three concrete mixes: control, 0.75% hemp, and 1.0% hemp. Eighteen beams in total were cast and tested.

1.7. Thesis Outline

The thesis is divided into seven chapters. Chapter 1 is an introduction and background on the topic of sustainable development and material, and a summary of the research program and objectives. Chapter 2 presents background and literature review on fiber-reinforced composites and previous research of fiber-reinforced concrete. Chapter 3 details the phases of the experimental research program and testing procedures. Chapters 4, 5, and 6 present, respectively, the results of: the preliminary trial phase, the first phase with statistical analysis and analytical linear models, and the second phase with the fibers incorporated in structural beam elements. Chapter 7 summarizes and concludes the research and includes recommendations.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1. Fiber-Reinforced Cement and Concrete

Fiber-reinforced cements are used for thin sheet-like products such as flat and corrugated sheets, sliding or cladding panels or buildings, shingles, slates and shakes for roofing, and pipes for non-pressurized water and sewer drainage. Whereas, fiber-reinforced concrete is used mainly in thick sections, plain concrete or conventionally reinforced concrete, such as slab on grade, overlays to existing slabs, and pneumatically applied shotcrete layers or linings to stabilize, protect or rehabilitate exposed soils, rock, or deteriorated concrete surfaces such as in tunnels. The minimum applied thickness is 50 mm.

The first use of Fiber-Reinforced Concrete (FRC) dates back to the 1870s. Since then, research work attempted to improve the tensile strength of concrete by adding iron waste, wood, steel wires, and other material. Fibers used in concrete were artificial such as steel, iron, carbon and others, and natural such as bamboo, jute, coconut, sisal, hemp and others. High performance fiber-reinforced concrete is intended to provide strength requirements, provide a durable concrete, and achieve a toughness behavior after the first crack point. The post-cracking behavior of fiber-reinforced concrete is of major interest. Compared to the plain concrete with no fibers, the fiber-reinforced concrete has a ductile behavior under tensile loading, whereas the plain concrete has a sudden failure after the maximum load is reached.

It is worth noting that fiber-reinforced concrete is made of the conventional concrete mix including aggregates, in addition to the fibers; whereas, fiber-reinforced cement is made of cement slurry or cement paste (or fiber-reinforced paste) in addition to fibers.

The production process of fiber-reinforced cement consists of mixing the fibers with cement-based slurry without coarse aggregate in order to avoid any possible damage that fragile fibers may suffer in regular concrete mixing with coarse aggregate included. Another range of fiber-reinforced concretes was made by including more robust discontinuous fibers as an ingredient of concrete in the conventional mixing process, in addition to other ingredients like aggregates and admixtures. Accordingly, the fiber content in concrete composites was much less than in cement composites, typically no more than 1.5 to 2% by volume and with longer fibers used (15-65 mm). The length and cross-section of fibers are greater than those used in fiber-reinforced cement, i.e. the length of fibers should exceed the maximum size aggregate. The problem is the matrix stiffening and workability in the presence of coarse aggregates. The mechanical mixing is very critical for the matrix mixing with the fibers and the coarse aggregates. Intensive mechanical mixing may damage and abrade the fibers. The use of fly ash or silica fume increases the paste volume and allows better fibers accommodation. The idea started with a French patent Alfsen in 1918, based on uniformly mixing small longitudinal fibers of iron, wood, or other materials into concrete. The fiber elements needed to be rough, with non-straight ends, in order to improve the pullout resistance of fibers from concrete. In the 1960s, smooth straight steel fibers produced by cutting wire or sheet metal became widely available commercially, which allowed for their wider use in the concrete industry. In addition to steel, other fibers were used such as polypropylene, polyethylene, and various types of polyester (Naaman, 1990).

The cement or concrete mixes enhancement level depends on the fiber type and content. It may include improvements in tensile or flexural strength, ductility, toughness, and energy absorption capability, impact resistance, fatigue resistance, cracking resistance, permeability, and durability. However, the designer should recognize that the amount of fibers present is a major factor influencing the extent and degree of property enhancement. Thus, the volume fraction of fibers per unit volume of the composite is fundamentally important when comparing the effects produced by different types of fiber, even though it is convenient for practical purposes to batch fibers by weight per unit volume of composite. The reason behind comparing different fibers using the volumetric method is because of the difference in the fibers density, i.e. polypropylene density is 910 kg/m^3 whereas steel density is 7,860 kg/m^3; consequently, it is unrealistic to compare different fibers only by weight.

Fibers affect composite properties in both the freshly mixed and hardened states, often in opposite directions. For example, increasing the fiber content tends to improve the degree of enhancement of many properties in the hardened state, but also decreases mixture workability in the freshly mixed state, until, at some maximum fiber content, the production and mixing is no more possible and the fiber distribution would not be uniform. Consequently, the hardened properties by using fibers cannot be totally achieved because of any non-uniform fiber distribution or improper consolidation, or both.

Another example is the conflicting role of fiber aspect ratio, which is the ratio of fiber length to diameter for straight circular fibers. In general, a higher fiber aspect ratio results in better reinforcing effectiveness and greater potential property enhancement in the hardened state than for the same amount (fiber content) of shorter thicker low aspect ratio. However, high aspect ratio also reduces mixture fluidity more severely than lower aspect ratio. Thus, mixtures with high aspect ratio are more difficult to produce in the freshly mixed state; whereas, low aspect ratio offers a better mixing capability in the freshly mixed state, but has little property enhancement in the hardened state. Consequently, there should be a compromise between the freshly mixed state and the enhanced properties at the hardened mixed state.

The applications of fiber-reinforced concrete cover a wide range of concrete work such as: in bulk structures where energy absorption is needed; in thin structures where additional strength and ductility are needed; in protective, blast, and impact resistant structures; and in bank vaults, pile caps, refractory applications, pavements, airfields, taxiways, bridge deck overlays, thin sheets and shells, cladding panels, tunnel lining, joint-hinges in concrete structures, and aerospace launching platforms. In all applications, FRC is used to improve static and dynamic tensile strength, energy absorption, toughness, and fatigue resistance.

For further reference on Fiber-Reinforced Cement and Concrete, the reader is referred to many available references such as the ACI committee report 544 on FRC (1996), in addition to other specific ACI committee reports about steel, glass fibers, and others. Text-books are also available such as “Fiber-Reinforced Cements and Concretes” by C.D. Johnston (2006), and many other textbooks dealing with high performance construction and advanced infrastructure materials.

2.2. Natural Fibers and Current Applications in Cement

Synthetic fibers and natural fibers have also been investigated and tried in both cement and concrete mixes. The advantage of using natural fibers, like jute, sisal, coconut, banana, hemp, and others in fiber-reinforced concrete is the saving on natural resources. Natural fibers are in most cases classified as waste materials compared to industrial or synthetic fibers that are produced from other raw materials.

Due to their large availability, low cost, and renewable resources, natural fibers were considered in fiber-reinforced cements. In developing countries, many types of locally available natural vegetable fibers have been used in cement-based composites. The preparation techniques are very basic, without pressure or dewatering, yielding comparatively low strength products intended for small building applications. The main advantage is the low cost of production, and the main disadvantage is the high absorption of the fibers, their vulnerability to chemical attack by cement alkalis, and the detrimental effects of some secondary fiber constituents on setting and hardening of the matrix.

Natural fibers may include stem or bast fibers such as jute, flax, ramie, sunn, kenaf, urenaa, elephant grass, hemp, and various woods. However, wood fibers are most common, after being processed in a pulp mill to remove lignin leaving cellulose fibers. Natural fibers can be incorporated in cement composites using the Hatscheck process (Johnston, 2006).

Manual or mechanical mixing can be accomplished by premixing cement, water and additives to form slurry, adding fine aggregates, and adding fibers last. Alternatively, the fibers may be pre-saturated and added to cement, sand and admixtures with little water to produce a dry stiff mixture compatible under pressure.

Most natural fibers contain glucose, which retards hardening of cement, and most are susceptible to rot as a result of bacterial or fungal action under moist condition. An accelerating admixture can be used to counter the effect of glucose. An organic microbiocide may be needed to prevent bacterial attack. Also natural fibers are prone to dimensional change during wetting and drying, because of their high absorption, and are subject to deterioration by alkalis action. The long term effectiveness of natural fibers depends on using treatments that reduce dimensional changes during wetting and drying, and using pozzolanic admixtures to lessen the alkalis attack.

2.3. Industrial Hemp Fibers

One natural fiber of interest is hemp. Hemp is the common name for plants of the entire family of Cannabis. Hemp is cultivated virtually everywhere in the world, and its cultivation in western countries is growing steadily. The use of hemp has been shown to date back thousand years in China and America (Allin, 2005). Industrial hemp is defined as the non-drug plant which substitutes its sister “illegal” hemp plant. Therefore, when grown for non-drug purposes, hemp is often called industrial hemp. Industrial hemp and its fibers have a large number of usages, including paper, textiles, biodegradable plastics, health food, and fuel. It is one of the fastest growing biomasses on the planet, and one of the earliest domesticated plants known. Hemp requires little to no pesticides, replenishes soil with nutrients and nitrogen, controls erosion of the topsoil, and produces a lot of oxygen, considering its fast rate of growth. Hemp can be used for a wide variety of purposes, including the manufacture of cordage of varying tensile strength, clothing, and nutritional products. The inner two fibers of hemp are woodier, and are more often used in non-woven items and other industrial applications, such as mulch, animal bedding and litter. The oil from the fruits dries on exposure to air and is sometimes used in the manufacture of oil-based paints, in creams as a moisturizing agent, in cooking, and in plastics.

Hemp fibers and hurds have been used in construction materials, such as the Hemcrete, produced in Europe as construction blocks with good strength and thermal insulation performance (Allin, 2005). Other applications include the use of hemp fibers instead of asbestos fibers with the cement mortar. Also, the inner core or the shive part of the harvested hemp plant is blended with materials like lime to produce hempcrete, a building composite suitable for the creation of walls, floors, roof insulation and plasters. Hemp-based products have been used for centuries in timber-framed buildings and for restoration.

2.4. Previous Research on FRC with Synthetic and Industrial Fibers

Research on synthetic and industrial fibers used in concrete mixes is amply available in the literature. This section will focus only on the previous work conducted at the American University of Beirut (AUB) due to its relevance as it will feed into the current experimental program.

Hamad et al. (2003) conducted two research programs to assess the effect of confinement provided for tension lap splices anchored in high strength concrete beam specimens on bond strength of the splices and mode of failure of the beams. In one program, loose hooked steel fibers (with aspect ratio of 30/0.5 = 60) of different volume fractions were used. In the second program, transverse reinforcement was placed in various amounts. Test results of both programs indicated positive effects of the confinement provided on the bond strength of the tension lap splices and on the mode of failure. It was concluded that the ductility of the mode of failure of the specimens improved as the amount of steel fibers or number of stirrups increased in the splice region. The post-ultimate load-deflection curves for specimens with steel fibers in the splice region were much steeper than those of companion beams with transverse reinforcement. There was a consistent increase in the average bond strength of tension lap splices as the fiber content in the splice region increased. The amount of steel fibers corresponding to a volume fraction of 1% improved the bond capacity of tension lap splices equivalently to that provided by transverse reinforcement.

Hamad et al. (2000) investigated the effect of steel fibers on the bond strength and ductility of the mode of bond failure of tension lap splices anchored in high strength concrete specimens. The test results indicated that the use of steel fibers in the splice region increased the bond strength and the ductility of the mode of failure of the beam specimens. This increase exceeded what can be achieved by using transverse reinforcement in the splice region.

Harajli et al. (1997) investigated the effect of fibers on development/splice strength of reinforcing bars in tension. The experimental results showed that the use of hooked steel fibers in concrete matrices increases significantly the development/splice strength of reinforcing bars in tension. While the use of polypropylene fibers improved the bond performance in the post-splitting range, they were not as effective as steel fibers.

2.5. Previous Research on Natural FRC

Most of the previous research on natural fibers applications has been conducted on fiber-reinforced cement rather than on fiber-reinforced concrete. Fiber-reinforced cements are mixes made of cement mortar in the absence of coarse aggregate.

Sedan et al. (2008) investigated the use of hemp fibers in reinforced cement. The influence on the setting time of cement was investigated in the presence of hemp fibers. The hemp fibers were provided by la Chanvrière de l'Aube, France. The fibers density was measured with pycnometer and was found equal to 1.53 g per cubic centimeter. In order to improve the adhesion in the cement matrix, the fibers were treated in different solutions prior to their use in the mix; the sodium hydroxide was the most commonly used chemical for cleaning the surface of plant fibers. The sodium hydroxide treatment changes the fibers mechanical properties, like the tensile modulus and strength, and their surface morphology. Fibers were soaked in a 6% NaOH water solution by weight, for 48 hours. Different short fiber contents were investigated, with the fibers lengths varying between 1 mm and 1 cm. Several conclusions were drawn from this study. The fiber presence in the cement matrix seems to trap calcium on their surface, thus resulting in a delay in the setting time because the calcium trap would inhibit the formation of the calcium silicates hydrate. As for the composite mechanical performance, an increase in the flexural strength was evident with optimal fiber content, whereas Young's modulus decreased in the fiber mix. Also, it was clear that the alkali treatment improved the fiber strength in addition to the fiber-matrix adhesion.

Elfordy et al. (2008) performed a research on concrete blocks made of a mixture of lime and hemp shives (also called hurds) using a projection process. The blocks thermal and mechanical properties were measured such as flexural and compressive strengths, and hardness. The thermal and mechanical properties were found to increase with the density increase. A compromise between thermal insulation and mechanical properties should be defined, depending on the type of construction. If non-structural elements are intended, then low thermal conductivity and low strength blocks are favored; whereas, if the blocks are part of the structural integrity then denser, stronger, but with lower insulation properties blocks are adopted.

Kymäläinen et al. (2008) evaluated the suitability of bast fibers of flax and hemp for thermal insulation. The research found that the flax and hemp fibers are suitable for insulations due to their thermal properties. However, these fibers tend to degrade in the presence of microbial and other contaminants. Besides, these materials may produce moulds under moist and free water weathering, which affects the indoor air quality of buildings.

Pickering et al. (2007) investigated the performance of hemp fibers in a polypropylene matrix composite. Hemp fibers were treated in 10% (by weight) NaOH solution which resulted in stronger fibers with a low lignin content and good fiber separation. The hemp fibers had an average tensile strength of 857 MPa and a Young's modulus of 58 GPa.

Li et al. (2006) studied the mechanical and physical properties of hemp fiber-reinforced concrete. In the experimental program, the variables were the mixing method, the fiber content by weight, the aggregate size, and the fiber length. The compressive and flexural performances were determined, in addition to the specific gravity and water absorption ratio. The hemp properties used were specific gravity (1.5), water absorption (85-105%), tensile strength (900 MPa), and modulus of elasticity (34 GPa). It was found that the compressive strength, flexural strength, toughness, specific gravity, and water absorption are all affected by the aggregate size, fiber factors, and matrix initial mechanical properties. Wet mixing method had a positive influence on the flexural properties more than dry mixing method.

Savastano et al. (2005) investigated the microstructure of composite materials with fibrous wastes such as sisal, eucalyptus grandis, and banana fibers. The cementitious material included blast furnace slag and ordinary cement matrices. Sisal and eucalyptus grandis pulps showed satisfactorily bonding to the cement matrix, with fiber pullout predominant and simulated by high values of energy absorption. On the other hand, banana fibers reinforced composites exhibited fiber fracture as failure mechanism. On all composites failure interfaces, partial fiber debonding and matrix micro-cracking were dominant. Besides, no evidence existed of a porous transition zone or massive concentration of calcium hydroxide at the interface.

Savastano et al. (2003) evaluated the performance of thin fiber-reinforced cements with sisal and banana fibers, produced using different processes. Granulated blast furnace slag was used as a major component of an alternative hydraulic binder and ordinary Portland cement as a control. It was found that after twelve months of exposure to temperate and tropical conditions, the modulus of rupture had decreased; whereas, the fracture toughness remained stable or even increased. The results indicated that the mechanical performance of the composites was satisfactory.

Tolêdo Filho et al. (2003) examined the durability of vegetable fibers in reinforced cement mortars. The research presented several approaches to improve the durability of sisal and coconut fibers reinforced cements. These approaches were such as carbonation of the matrix in a CO_2-rich environment, the immersion of fibers in silica prior to incorporation in the cement matrix, partial replacement of ordinary cement with undensified silica fume or blast furnace slag, and a combination of fiber immersion in slurried silica fume and cement replacement. The durability was examined by determining the effects of ageing in water, exposures to cycles of wetting and drying and open air weathering on the microstructure and flexural behavior of the composites. Immersion in silica fume slurry before incorporation on the cement matrix was found to be effective. Carbonation of the matrix and the partial replacement of cement were also effective. The use of slag as a partial cement replacement had no effect on reducing the embrittlement of the composite.

In a research conducted at the American University of Beirut (AUB), Hamad et al. (2003a and 2003b) considered the use of wastes in the production of concrete such as the car motor engine oil. Consequently, a “sustainable” concrete was prepared since it resulted in a positive environmental impact by reducing the cost of waste disposal while improving the properties of concrete material. First, Hamad et al. (2003a) investigated the effect of using car engine oil on the properties of fresh and hardened concrete. The main variables incorporated in the study were the type and dosage of an air-entraining agent (such as commercial type, used engine oil, and new engine oil), mixing time, and the water cement ratio of the concrete. Tests results showed that the used engine oil increased the slump and percentage of entrained air of the fresh concrete mix, and did not adversely affect the strength properties of hardened concrete. Further, Hamad et al. (2003b) reported the effect of car engine oil on the structural behavior of reinforced concrete elements. Three modes of failure were investigated; flexure, shear, and bond. The tests results, regardless of the failure mode, showed that the used engine oil did not have any significant effect on the ultimate load or load-deflection behavior of the beams.

Tolêdo Filho et al. (2000) assessed the durability of sisal and coconut fibers when exposed to alkaline solutions of calcium and sodium hydroxide. Also the durability and microstructure of the cement mortar composites with these fibers aged under tap water, exposed to controlled cycles of wetting and drying and open air weathering, were investigated. It was found that sisal and coconut fibers kept in a calcium hydroxide solution of PH 12 completely lost their flexibility and strength after

300 days. The cement composites suffered a significant reduction in toughness after six months. The embrittlement of the composites was mainly associated with the mineralization of the fibers due to the migration of hydration products, especially calcium hydroxide to the fiber lumen, walls and voids.

Al Rim et al. (1999) investigated the influence of wood aggregates on thermal and mechanical performance of clay-cement-wood composite. It was found that the addition of wood to the clayey concrete increases the thermal conductivity, decreases the mechanical strength but increases the deformability. However, the durability of wood particles in clayey concrete could be affected by the composite humidity.

Garcia-Jaldon et al. (1998) investigated the processing of hemp fibers by steam explosions. In this research, it was mentioned that the hemp density was 1.48 kg/m^3, and tensile strength 0.7 GPa, modulus of elasticity 32 GPa, and an elongation at break of 2%.

It is worth noting that research work have been also conducted on the hybrid FRC material, where more than one type of fibers can be combined simultaneously in cement or concrete matrices. However, since this area of research is beyond the scope of the current thesis, further discussion will not be included here.

Major findings of the above listed literature review can be summarized as follows:

1. Sedan (2008): the flexure strength increased while both the elastic and shear moduli decreased with hemp addition.
2. Elfordy (2008): the thermal conductivity and mechanical strength increased with density with lime and hemp mixes.

3. Li (2006): the compression, specific gravity, and water absorption decreased with hemp addition. The fibers content affected both compression and flexure.
4. Savastano (2003): under 12 Months Exposure, the modulus of rupture decreased and the mechanical properties were satisfactory.
5. Tolêdo Filho (2003): some treatments were efficient against durability problems with vegetable fibers.

Based on the literature review, the majority of research work focused on the incorporation of natural fibers in mostly cement/mortar mixes more than in concrete or in reinforced concrete mixes, and without consideration of any reduction in aggregates quantities. In the current research program, the use of industrial hemp fibers is primarily investigated, in addition to other natural fibers such as banana and palm, and other synthetic fibers tested for comparison purposes. The core of the research focuses therefore on the hemp fibers, and the possibility of introducing in reinforced concrete buildings or other structural applications.

2.6. Chapter Summary

The fiber-reinforced cements and concretes have different specifications than conventional concrete. Due to the presence of fibers in the cement or concrete matrix, both the fresh and hardened states of cement and concrete materials are different and need special considerations. Fiber-reinforced cement or concrete applications vary from thin sheets, cladding panels, and pipes to slabs on grade, overlays, and shotcrete. Industrial hemp fibers are characterized by being a waste product, easily and rapidly harvested almost everywhere worldwide. Hemp fibers have been investigated and used in construction materials.

International researchers have published, in the late years, fiber-reinforced cement and concrete studies. Investigated fibers included synthetic and natural fibers. Natural fibers were investigated only in cement matrices rather than in concrete matrices.

Previously, local work considered only synthetic fibers such as steel and polypropylene fibers, in addition to car motor engine oil in concrete matrices. The natural fibers were not yet investigated locally.

In the following chapter, the research program will be described and detailed.

CHAPTER 3

RESEARCH PROGRAM

3.1. Introduction

As indicated in the previous chapters, the current research targets specific sustainability aspects such as saving natural raw materials while providing an acceptable concrete quality. The research incorporates the use of natural fibers in the concrete mixes, such as banana, palm, and hemp fibers, with emphasis on the latter. The objective of this research is therefore to identify new materials or create novel cement/concrete mixes that encapsulate sustainable elements while satisfying strength and improving performance requirements such as durability and thermal properties. The program set for this research should therefore encompass these aspects.

3.2. Fiber-Reinforced Concretes Specifications and Applications

The FRC specifications vary depending on their applications, and they include the fibers content, length, and type. The compressive strength is only adopted for some applications. However, in most cases, the performance criteria cover the flexural strength as first-crack and ultimate modulus of rupture (MOR), toughness to assess energy absorption, and residual strength retained after a specified amount of deflection has been sustained. For simplicity, flexural performance is usually based on simply supported beams; however, two-way slab test may be more representative for many applications.

For fiber-reinforced concrete, the main advantage is the load defection behavior in the post-cracking state, i.e. toughness. Toughness is not easily assessed and appreciated by designers, except when the structure is designed for earthquake and blast resistance, or any other dynamic load and post cracking resistance.

The durability problem is of concern with high fiber content, when the aim of usage is strength and toughness improvement; whereas at low content it is not a problem if the usage is just for plastic shrinkage after placement. The fiber-reinforced cements and concretes covered a large area of applications. It is worth noting that the fibers applications included in most cases industrial and synthetic fibers. Still, natural fibers did not find their way to large practical applications, mainly due to their durability problems in alkaline and moist environment. Yet, as reported in the previous chapter research has been conducted to investigate the use of natural fibers in fiber-reinforced cements more than fiber-reinforced concretes. However, if sustainable concepts and methodologies are to be adopted in upcoming engineering projects to adverse the effect of extensive depletion of natural resources, natural fibers will be the most widely sought element to use in concretes. These natural fibers are of low cost and considered in most cases as waste materials, whereas, all other non-natural fibers are of higher cost and are not considered as waste material.

The composite behavior between the cement/concrete matrix and the fibers depends on both the fibers and the surrounding matrix. The hardened state composite behavior is related to the freshly state of the mix and the fiber; i.e. need to assure that the mixing process was adequate, the fibers were not damaged, the amount and type of fibers were suitable and sufficient, and the fibers are uniformly distributed. Any combination of poor consolidation, fiber clumping or balling, fiber damage during mixing, or chemical incompatibility of fiber and matrix can ruin the composite performance of individual good quality raw materials. Thus, to monitor fiber-reinforced concrete mixes, both the fresh and hardened must be investigated and tested.

3.3. Research Program

The current research is a multi-phase program consisting of 3 main stages, which will be conveniently referred to as the trial, first, and second phases. The variables considered were the fibers volume fraction and the percentage of coarse aggregate reduction.

In the trial phase, different concrete mixes are investigated incorporating all above mentioned natural fibers (banana, palm, and hemp) in addition to polypropylene and steel fibers, as well as control mixes with no fibers. Based on the trial phase results, only the hemp fiber was adopted to proceed with the research, while the remaining fibers were excluded for many reasons such as availability and performance. In phase one, a full set of concrete mixes, with and without fibers, was prepared and specimens were tested for early and late strength properties. The first phase mixes included one control mix with no fibers, a concrete mix with polypropylene fibers, and ten mixes with different volumetric fractions of hemp fibers. A statistical analysis was also processed on phase one results for validation purposes. In phase two, structural beam elements were designed and prepared; the beams were tested for flexure, shear, and bond modes of failure. Two beam specimens were prepared for each test. Three mixes were considered, based on the results of the first phase, a control mix and two different mixes with different fractions of hemp fibers.

In summary, the trial phase mixes included 68 beams (5 x 5 x 20 cm) and 66 cubes (7 cm), the phase one mixes encompassed a total of 180 cylinders (15 x 30 cm), 72 beams (15 x 15 x 53 cm), and 12 blocks (5 x 30 x 30 cm), and the phase two mixes included eighteen beams (20 x 30 x 200 cm).

3.3.1. Trial Mixes Phase

The aim of the trial mixes phase was to investigate and pre-determine a concrete mix that can be adopted with the added fibers, provided that the strength and workability requirements are still satisfied after the fibers addition. Thus, many mixes had been tried, where the aggregate quantities were varied. One concrete mix was also adopted as a control mix with no fibers additive or aggregate reduction. Then after, the different fibers were added and the flexural and compressive strengths of beam and cube elements were tested, respectively.

3.3.1.1. Concrete Mix

Concrete trial mixes with different volumetric ratios of natural admixtures were prepared to assess the adequacy and practicality of mixing with natural. In all trial mixes, a unique concrete mix was adopted. The batching weights per cubic meter of concrete were: 880 kg medium coarse aggregate, 810 kg sand, 400 kg cement, and 272 liters water (w/c = 0.68). The super-plasticizer SIKA brand – type NN was used. A super-plasticizer dosage of 1.5% by weight of cement was added.

The coarse aggregate used is medium size, with oven-dry density of 1,600 kg/m^3 and a maximum size aggregate of 10 mm. The sand aggregate has a sand fineness modulus of 2.42, and a sand equivalent of 76. The cement is a general use (GU) type, according to ASTM C150, the specific surface area is 295 m^2/kg (Air permeability Blaine Test).

3.3.1.2 Fibers Characteristics

The fibers used in the trial mixes are: polypropylene, steel, banana, palm, and hemp fibers. Harbourite® 320 polypropylene fibers are used, with a density of 910 kg/m^3 and with Young's modulus 3,500 MPa. Dramix ZP 305 Steel fibers are used, with a density of 7,840 kg/m^3 and tensile strength 1,100 MPa. The hemp fibers have a density of about 1,400 kg/m^3. The palm fibers density is estimated about 800 kg/m^3. The banana fibers density is estimated about 700 kg/m^3. The fibers aspect ratio (L/d) is on average targeted to be 50 with a length (L) of 3 cm and a diameter (d) of 0.6 mm. Note that, for synthetic fibers, the aspect ratio can be accurately controlled; however, with natural fibers it is not the case, due to the variability in both dimensions. All natural fibers were processed manually. The palm and banana fibers were cut from raw tree leaves; whereas, the hemp fibers were imported as long fibers, then cut manually to 3 cm long.

Based on the literature review (Sedan 2008), the natural fibers were treated and soaked in a sodium hydroxide solution (NaOH) at 6% by weight for 48 hours. After soaking, the fibers were washed with water and left to dry, and then separated using a mechanical tool (refer to Figure A3.28). The industrial hemp fibers were imported from Stemergy Renewable Fibre Technologies, Canada. One trial mix was prepared with local hemp fibers, provided by the UNDP/MoA project. Note that in the trial mixes phase, some mixes were tried with untreated fibers; however, the performance of the fibers was not acceptable in terms of the bond with surrounding matrix, and thus the flexural performance did not improve compared to the plain mixes.

As an example on the volumetric ratio of the fibers, if a parameter of 1% is used it implies that the corresponding fibers volume is determined as 1% of the concrete volume. Then the fibers weight is determined by multiplying the fibers volume by the fibers density. Similarly, for the coarse reduction percentage, if a parameter of 10% is mentioned, it implies that the corresponding reduced coarse aggregate amount is 10% of the concrete volume. The aggregate weight is therefore determined by multiplying the aggregate volume by the aggregate density.

It is worth noting that the hemp percentages used in the concrete mixes of all research phases are calculated according to a hemp density of 1,400 kg/m^3.

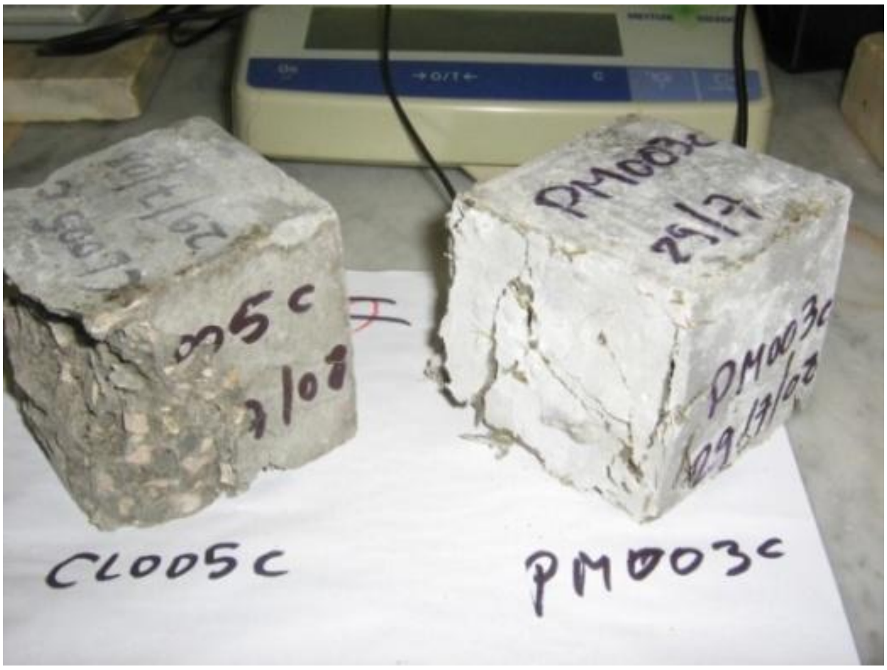
3.3.1.3. Trial mixes Tests

The trial mixes specimens included beams (5 x 20 x 20 cm) and cubes (7 cm), which were tested at 10 and 28 days for flexural and compressive strengths, respectively. As presented in Table 3.1, seventeen trial mixes were prepared. The added fibers included polypropylene, steel, hemp (imported and local), palm, and banana fibers. The fibers volumetric fraction was varied, in addition to the coarse aggregate reduction in some of the trial mixes. Typical tested specimens are shown in Figure 3.1.

Table 3.1. Identification of Trial Mixes for Cubes and Beams, at 10 and 28 Days.

Mix No.	Mix Type	Fibers (%Vol)	Aggregate Reduction (%Vol)	Test Specimens			
				Cube 10d	Beam 10d	Cube 28d	Beam 28d
1	1%Polypropylene	1.0	-	1	1	1	1
2	0.5%Steel	0.5	-	1	1	1	1
3	Control	-	-	1	1	1	1
4	Control	-	-	3	3	3	3
5	Control	-	-	2	2	2	2
6	0.5%Hemp	0.5	-	1	1	1	1
7	0.5%Hemp-10%coarse	0.5	10	2	2	2	2
8	0.5%Hemp-20%coarse	0.5	20	2	2	2	2
9	0.75%Hemp	0.75	-	2	2	2	2
10	0.75%Hemp-20%coarse	0.75	20	1	2	2	2
11	1%Hemp-20%coarse	1.0	20	1	2	2	2
12	0.5%Local Hemp	0.5	-	2	2	2	2
13	0.5%Palm	0.5	-	3	3	3	3
14	0.5%Palm-10%coarse	0.5	10	3	3	3	3
15	0.5%Palm-20%coarse	0.5	20	3	3	3	3
16	1%Palm	1.0	-	2	2	2	2
17	1%Banana	1.0	-	2	2	2	2

Flexure Beam (20 x 5 x 5 cm) Test



Compression Cube (7 cm) Test

Figure 3.1. Typical Trial Mixes Flexure and Compression Tested Specimens.

The objective of the trial mixes was to identify the performance of the added fibers in order to proceed with in the main research phases. Thus, the number and type of specimens was not always uniform, since after these preliminary trial mixes were completed, a full set of mixes and tests was performed in the next phases, as the main core phases of the research.

3.3.2. Phase 1 Mixes

Based on the trial mixes test results, the hemp fibers showed the best strength behavior. Consequently, only hemp fiber was adopted. Besides, the hemp fibers are readily available and can be bought at an affordable cost; whereas, the palm and banana fibers were processed manually from the tree leaves which is not practical when large quantities are needed.

In the first phase, the industrial hemp fibers were provided locally by the UNDP/MoA project, or were imported from Hemptraders, LA, USA. Hemp fibers typical properties were supplied by Hemp Traders report (Serbin, 1993), i.e. the ultimate tensile strength was reported as 524 MPa (76,000 psi). Also, according to Sedan (2008), it was reported that the hemp fibers has a modulus of elasticity of 38 to 58 GPa and a tensile strength of 591 to 857 MPa. Fibers length and diameter varied and were on average 30 mm and 0.6 mm, respectively.

3.3.2.1. Concrete Mix

As mentioned earlier, the batching weights per cubic meter of concrete were the same in all phases as in the trial phase. The batching weights per cubic meter of concrete were: 880 kg medium coarse aggregate, 810 kg sand, 400 kg cement, and 272 liters water (w/c = 0.68). Only the super-plasticizer dosage was increased to 2% by weight of cement, instead of 1.5% for trial mixes.

3.3.2.2. Phase 1 Tests

The aim of phase 1 mixes was to optimize a concrete mix with the proper fibers volume ratio and an adequate coarse aggregate reduction. The optimum concrete mix would be used in larger and structural specimens, in phase 2. The variables of phase 1 included the volumetric ratio of the added fibers, and the reduction in the amount of coarse aggregates measured as a percentage of the volume of concrete. Twelve mixes have been prepared including control, polypropylene mixes, and different hemp mixes. The mixes variables are presented in Table 3.2.

Several tests were conducted using the prepared twelve mixes: flexure strength test using standard beams (15 x 15 x 53 cm), compressive strength test using standard cylinders (15 x 30 cm), splitting tensile strength and modulus of elasticity using standard cylinders, and thermal conductivity test using a block specimen (5 x 30 x 30 cm). In addition to slump test at the freshly concrete mixed state, and the density test at the hardened state.

Table 3.2. Identification of Phase 1 Mixes for Cylinders (15 x 30 cm), Beams (15 x 15 x 53 cm), and Thermal Blocks (5 x 30 x 30 cm).

Mix No.	Mix Type	Fibers (%Vol)	Aggregate Reduction (%Vol)	Cylinders	Beams	Blocks
1	Control	-	-	15	6	1
2	0.5%Polypropylene	0.5	-	15	6	1
3	0.5%Hemp	0.5	-	15	6	1
4	0.5%Hemp-10%coarse	0.5	10	15	6	1
5	0.5%Hemp-20%coarse	0.5	20	15	6	1
6	0.5%Hemp-30%coarse	0.5	30	15	6	1
7	0.75%Hemp-10%coarse	0.75	10	15	6	1
8	0.75%Hemp-20%coarse	0.75	20	15	6	1
9	0.75%Hemp-30%coarse	0.75	30	15	6	1
10	1%Hemp-10%coarse	1	10	15	6	1
11	1%Hemp-20%coarse	1	20	15	6	1
12	1%Hemp-30%coarse	1	30	15	6	1

Figure 3.2. Typical Standard Cylinder (15 x 30 cm) Tested According to ASTM C39.

- Compressive Strength Test – ASTM C39

According to ASTM C39, standard cylinders (15 x 30 cm) were tested to determine the compressive strength of phase 1 mixes at 3, 7, and 28 days. Three specimens were tested per test and their average was determined, i.e. 108 cylinders were tested for the compressive strength test. Figure 3.2 shows a typical tested standard cylinder.

- Flexure Beam Test – ASTM C78

According to ASTM C78, beam specimens (15 x 15 x 53 cm) were tested in order to determine the load deflection curves of all concrete mixes. The beam specimens were tested using the MTS machine, where the load P (kN) is applied simultaneously at 2 locations, 15 cm apart, symmetric with respect to the beam mid-span. Figure 3.3 shows a typical beam specimen with the testing set up.

- Splitting Tensile Strength Test – ASTM C496

According to ASTM C496, standard cylinders (15 x 30 cm) at 28 days were tested under a splitting tensile load until failure. Three specimens average were considered for every test. A typical splitting tensile test specimen is shown in Figure 3.4.

- Modulus of Elasticity Test – ASTM C469

The modulus of elasticity was measured, according to ASTM C469, for all mixes. Standard cylinder specimens 15 x 30 cm are used. The average of three specimens was determined. Figure 3.5 shows a typical modulus of elasticity test set up.

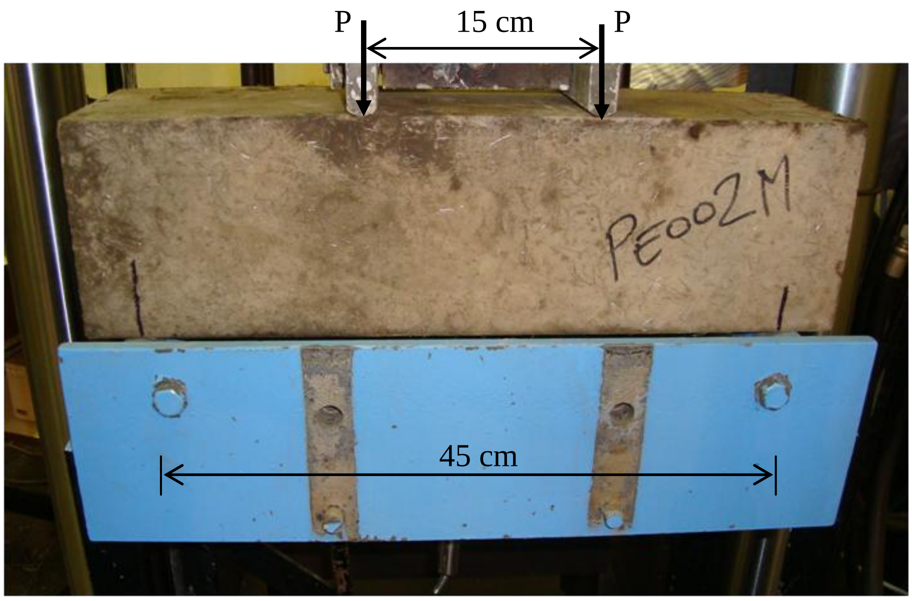


Figure 3.3. Flexure Beam Specimen (15 x 15 x 53 cm) Test With the Loading Set Up.

Figure 3.4. Splitting Tensile Test Specimen (15 x 30 cm), Longitudinal and Side Views of the Test Set Up.

Figure 3.5. Modulus of Elasticity Test Specimen (15 x 30 cm).

Figure 3.6. Thermal Conductivity Test Block (5 x 30 x 30 cm) Set Up.

- Thermal Conductivity Block Test – ASTM C518

The thermal conductivity of the concrete mixes was determined according to ASTM C518. For every mix, one block (5 x 30 x 30 cm) was tested. Figure 3.6 shows a typical thermal conductivity test set up.

- Density Test – ASTM C642

The density test was performed at the hardened state according to ASTM C642.

3.3.3. Phase 2 Mixes

In the second and last phase of the research, structural members were cast and tested. The focus was only on hemp fibers. One control mix with no fibers was prepared, in addition to two hemp mixes which were selected based on the first phase test results and performance. One mix with a 0.75% hemp volume fraction in addition to a coarse aggregate reduction of 20% by volume of concrete (0.75%Hemp-20%coarse), and another mix with 1% hemp volume fraction and a coarse aggregate reduction of 20% by volume of concrete (1%Hemp-20%coarse). The mixes selections considered the strength properties and workability of the concrete.

In this phase, the performance of the fiber-reinforced concrete using hemp fibers was tested for flexure, shear, and bond modes of failure. For every mode of failure, two beams were cast and tested for a better specimen representation and test validity, thus 6 beams were prepared for every mix. Eighteen beams were prepared and tested in this second phase.

3.3.3.1. Concrete Mix

As in other phases, the batching weights per cubic meter of concrete were the same in all phases as in the trial phase. The batching weights per cubic meter of concrete were: 880 kg medium coarse aggregate, 810 kg sand, 400 kg cement, and 272 liters water (w/c = 0.68). The super-plasticizer dosage was 2% by weight of cement.

3.3.3.2. Phase 2 Tests

In phase two, two of the best mixes found in phase one were selected, and were used in casting large scale structural elements. Large scale specimens are all beam elements, with different reinforcement details to take into consideration flexure, shear, and bond failure modes. The dimensions of the beam specimens are 200 cm length, 30 cm depth, and 20 cm width. The beams reinforcement bars were designed depending on the required mode of failure, based on the American Concrete Institute (ACI). For instance, for a flexure mode of failure, the shear reinforcement was sufficiently provided to ensure that the beam specimen will fail under flexure and/or shear. For the shear failure mode, stirrups were provided less than the minimum requirements of ACI-08-Section 11, in order that failure occurs in the shear zone and not under flexure. Similarly, for the bond failure, spliced bars were provided at the beam center with a minimum spliced length of 30.5 cm, less than the recommended length by ACI-08-Section 12.2 requirements. As shown in Figure 3.7, on top of the beam surface, a third-point loading set up was used, a load P was applied simultaneously at two locations, 60 cm apart, symmetric with respect to the beam center point (total machine load is 2P), the middle 60 cm strip constitutes a pure flexure zone,. The beam clear span (L) is 180 cm and the beam total length (L') is 200 cm. Accordingly, the different beams reinforcement details are shown in Figure 3.8.

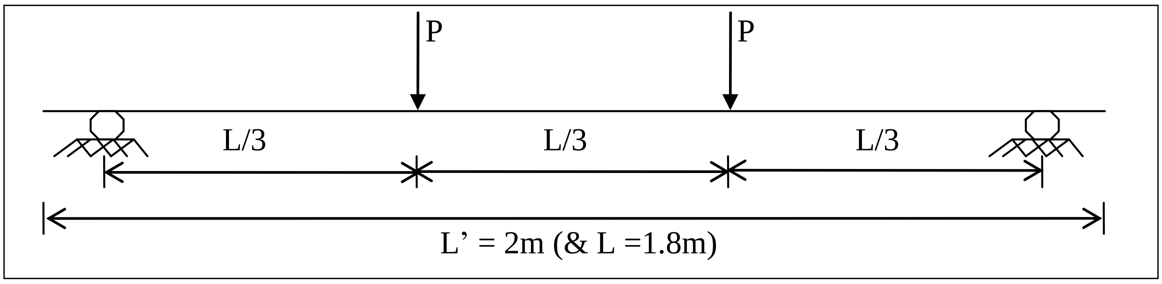


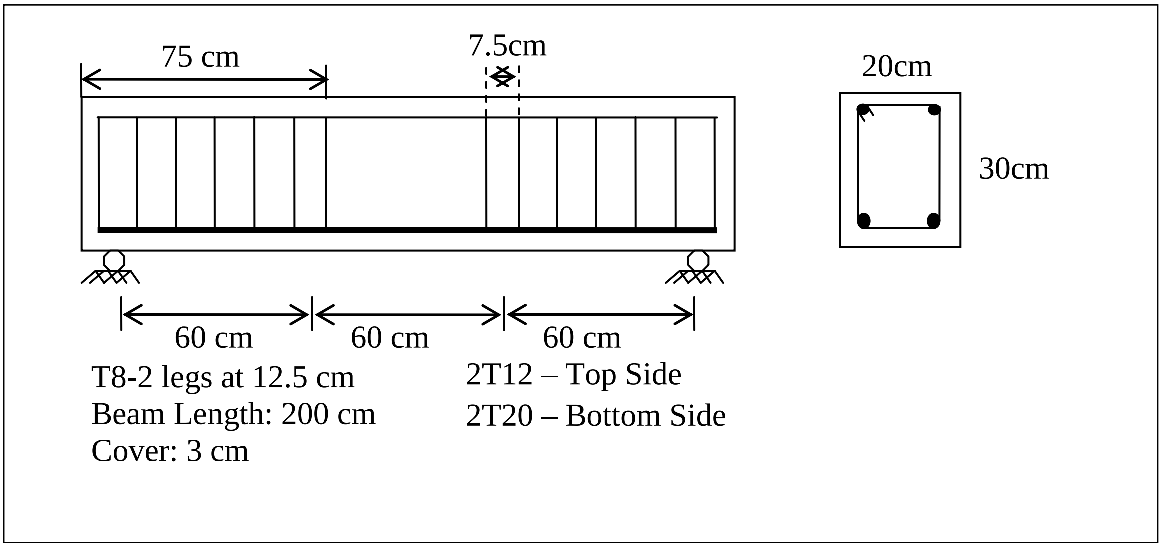
Figure 3.7. Beam Test Third-Point Loading Set Up (Machine Total Load is 2P).

- Flexure Beams

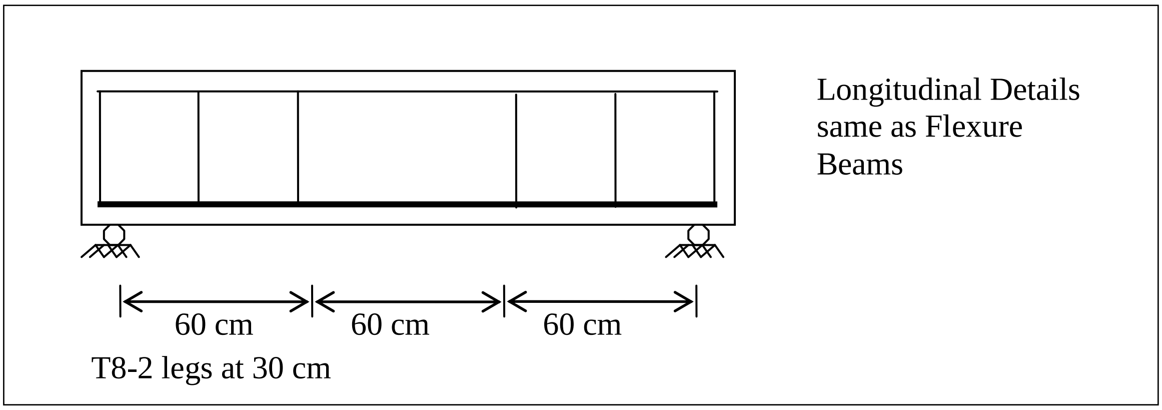
For the flexure beam specimens set, six beams were prepared for the three mixes, i.e. two beams for every mix type. As shown in Figure 3.8 and according to the ACI design requirements, the beam was designed to carry a load (2P) of about 19 Tons (about 190 kN).

The design criteria are on average: concrete compressive strength 200 kg/cm^2, Grade 60 Steel, beam width 20 cm, beam height 30 cm, depth to tension reinforcement 25 cm, depth to compression reinforcement 5 cm, and concrete cover 4 cm (1.5 inches). The reinforcement details are 2T20 mm on bottom side and 2T12 mm on top side. Shear reinforcement consist of 7 stirrups on every side, everyone is a 2-legs 8 mm bar. Note that to satisfy the ACI shear design (Chapter 11) requirements, 2 legs - T8 mm stirrups at 18 cm spacing are needed, and the maximum spacing allowed is 12.5 cm (d/2).

FLEXURE BEAMS – 6 BEAMS



SHEAR BEAMS – 6 BEAMS



BOND BEAMS – 6 BEAMS

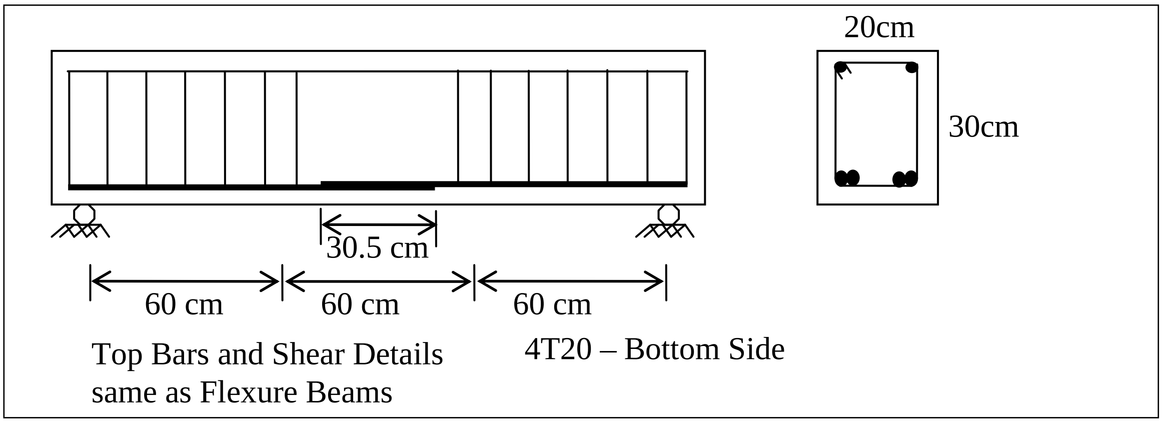


Figure 3.8. Structural Beam Specimens Details for Flexure, Shear, and Bond Modes of Failure.

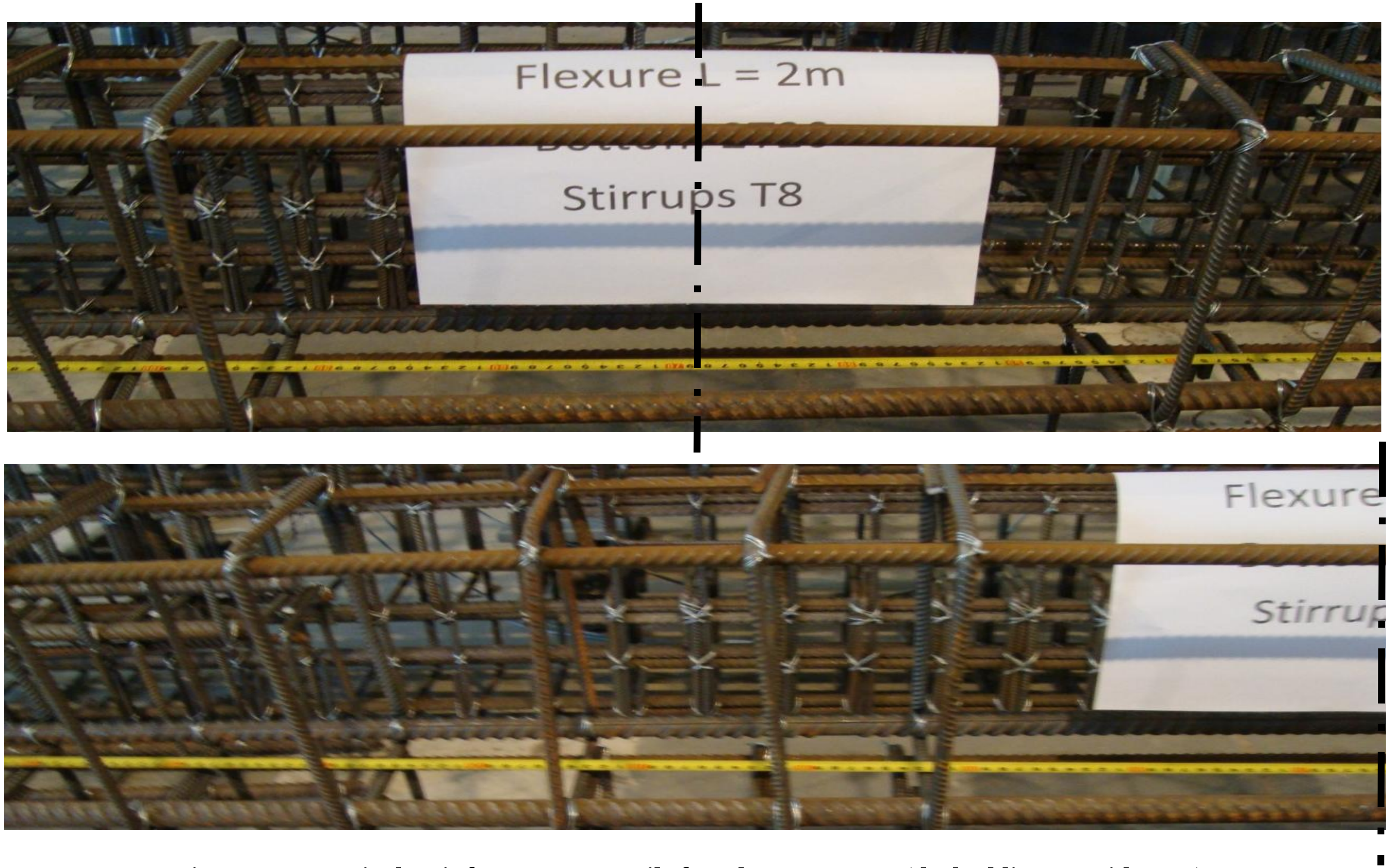


Figure 3.9. Typical Reinforcement Details for Flexure Beams (dashed line at Mid-span).

The test was performed consistently on all beams as follows. The load was applied simultaneously as P, 60 cm apart, as shown in Figure 3.5. The deflection was measured at mid-span of tested beam. The crack width was measured at 2 or 3 locations, depending on the mode of failure. To monitor the reinforcement elongation, two strain gages were attached to the bottom reinforcement bars, one on each T20 mm bar. Figure 3.9 shows a typical flexure beam reinforcement details.

- Shear Beams

For the shear beam specimens set, six beams were prepared for the three mixes, i.e. two beams for every mix type. As shown in Figure 3.8, and according to the ACI design requirements, the beam specimens were reinforced with shear reinforcement less than the required, in order to make sure that the failure will occur in the shear zone. The longitudinal reinforcement was kept the same as that of the flexure beams. The shear reinforcement was reduced to only six two-legs 8 mm bar, 3 on every side as shown in Figure 3.8. Thus, the beams would fail under shear load before the maximum flexure load is reached.

Similarly to the flexure beams, the test was performed consistently on all beams as follows. The load was applied simultaneously as P, 60 cm apart, as shown in Figure 3.7. The deflection was measured at mid-span of tested beam. The crack width was measured at 2 locations, mid-span and under one of the load P (left or right, whichever started first). To monitor the reinforcement elongation, two strain gages were attached to the bottom reinforcement bars, one on each T20 mm bar. Figure 3.10 shows a typical shear beam reinforcement details.

Figure 3.10. Typical Reinforcement Details for Shear Beams (dashed line at Mid-span).

- Bond Beams

For the bond beam specimens set, six beams were prepared for the three mixes, i.e. two beams for every mix type. As shown in Figure 3.8, and according to the ACI design requirements, the beam specimens were reinforced two splices T20 mm symmetric with respect to the beam mid-span and 30.5 cm long. Note that to satisfy ACI splice (chapter 12.2) minimum length requirement, the minimum length required is: $33.6*d_b = 67.2$ cm.The splice length used is below the required and is the minimum allowed (30.5 cm or12 inches).

Similarly to the other beams, the test was performed consistently on all beams as follows. The load was applied simultaneously as P, 60 cm apart, as shown in Figure 3.7. The deflection was measured at mid-span of tested beam. The crack width was measured at 3 locations, mid-span and at the splice ends (left and right). To monitor the reinforcement elongation, two strain gages were attached to the bottom reinforcement bars, one on each T20 mm bar, and another at one of the splice ends. Figure 3.11 shows a typical bond beam reinforcement details.

- Reinforcement Bars Elongation and Yield Limit

To determine the strain and thus the yield limit of the bottom reinforcement bars, one strain gage was fixed on every T20 mm bar, as mentioned above. For the location of strain gages, for flexure and shear beams, all gages were located approximately at mid-span; whereas, for the bond beams, the gages were located at the splices end, diagonally opposed (on one bar left and on another right, or vice versa), as shown in Figure 3.12.

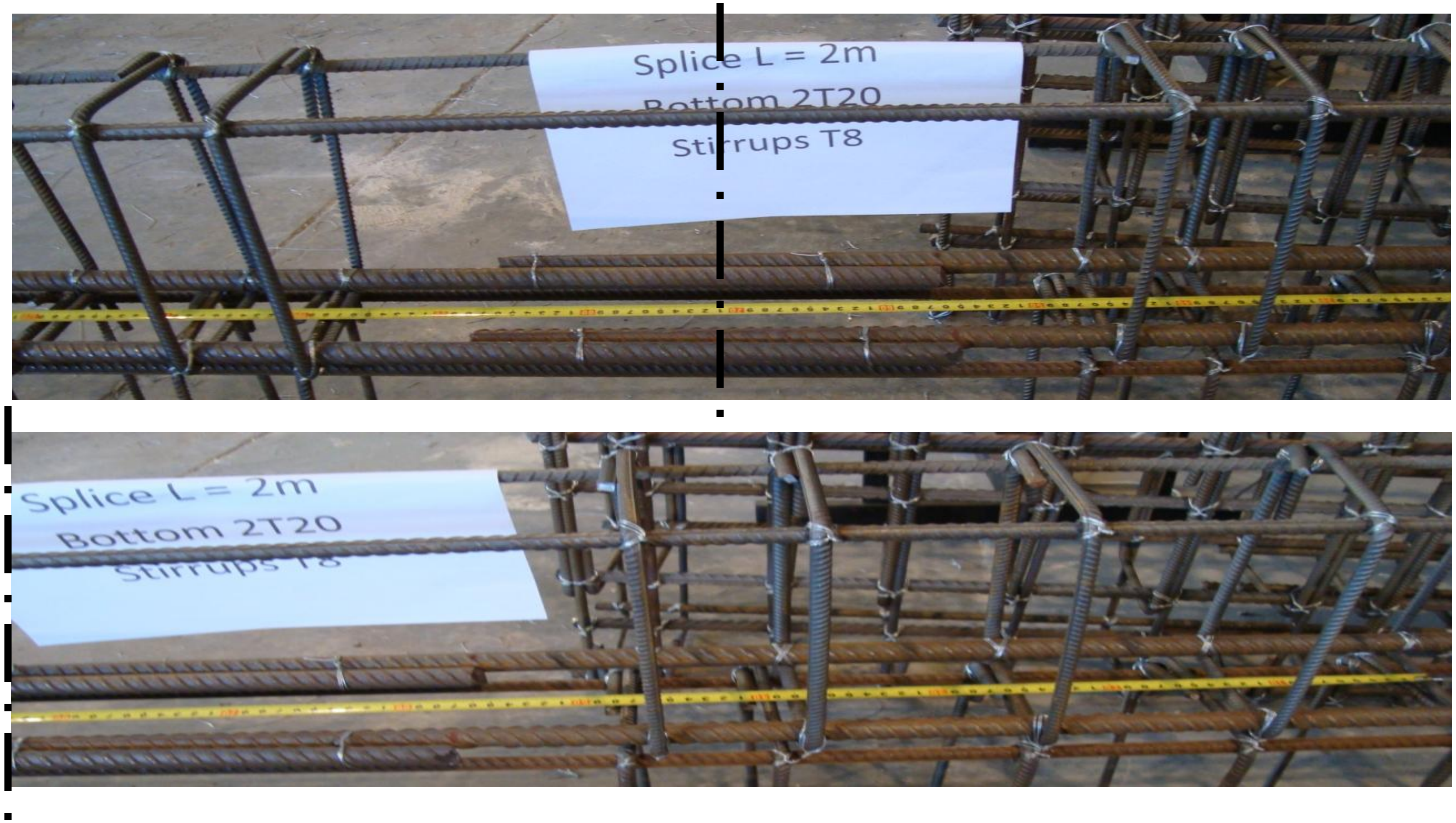
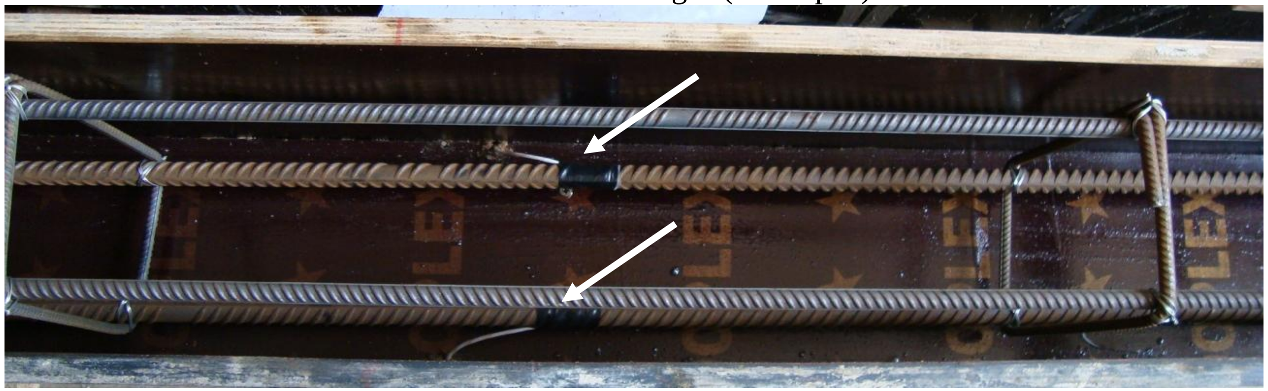


Figure 3.11. Typical Reinforcement Details for Bond Beams (dashed line at Mid-Span).

Flexure and Shear Gages (Mid-Span)



Bond Gages (Splice End)

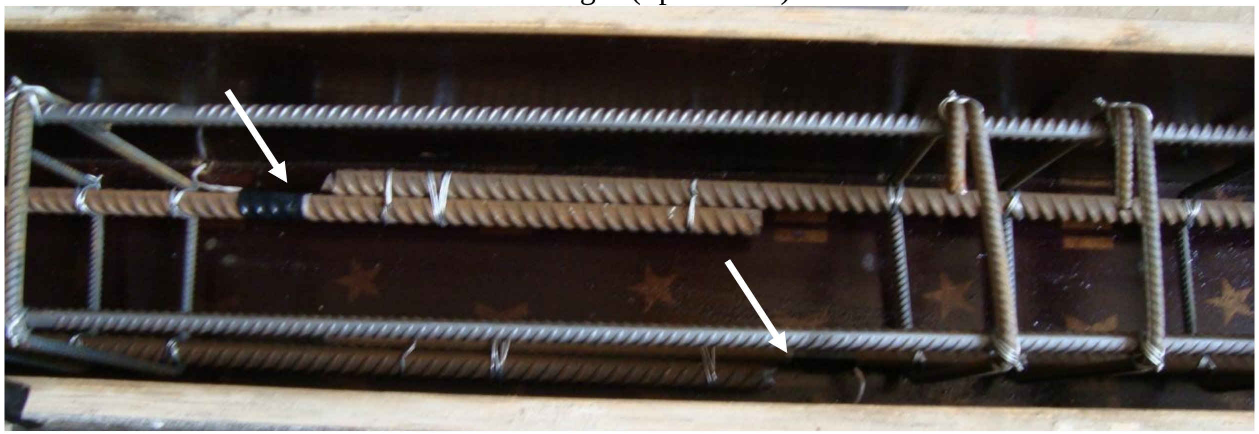


Figure 3.12. Strain Gages Layout for Flexure and Shear Beams, and Another Layout for Bond Beams.

3.4. Summary and Conclusion

The research is a multi-phase program consisting of 3 main stages. In the trial mixes phase, different concrete mixes in addition to synthetic and natural fibers were prepared. The compression and flexure properties of small specimens were determined. In the following first phase, a full-scale testing set of concrete mixes properties was targeted. A unique concrete mix was adopted based on the trial phase results. A control mix and a polypropylene mixes were included for comparison purposes, in addition to only hemp fibers mixes, where the fiber volume fraction was varied between 0.5, 0.75, and 1% and the coarse reduction varied between 10, 20, and 30% by volume of concrete. In phase one, flexure, compression, splitting tensile, modulus of elasticity, and thermal conductivity on standard ASTM specimens were performed; in addition to the slump test at the fresh state and density test at the hardened state. In the final phase, three concrete mixes were considered to monitor the hemp fiber-concrete mix in beam structural elements. One control mix and two other hemp fibers mixes. The beam elements were designed to be tested under flexure, shear, and bond modes of failure. Two specimens are prepared for every test for a better representation and test validity. In the following chapters (4, 5, and 6), the results of every phase of the research are presented and analyzed.

CHAPTER 4

TRIAL MIXES PHASE

4.1. Introduction

The research trial phase described in Chapter 3 was set in order to investigate the possible natural fibers that can be used in concrete mixes, and their availability. Banana, bamboo, palm, and industrial hemp fibers were prepared and used in concrete mixes. The monitoring tests are compression cubes (7 cm) and flexure beams (5 x 5 x 20 cm). The trial mix phase results are presented and illustrated in adequate tables and figures in this chapter.

4.2. Trial Mixes Tests Results

The trial mixes included 68 beams (5 x 20 x 20 cm) and 66 cubes (7 cm), tested at 10 and 28 days for flexural and compressive strengths, respectively. The compression cube test is according to ASTM C39 (2010) and the flexure beam test is according to ASTM C78 (2010). The added fibers included polypropylene, steel, hemp (imported and local), palm, and banana fibers. The fibers volumetric fraction was varied, in addition to the coarse aggregate reduction in some of the trial mixes.

It is worth noting that prior to adopting a unique concrete mix in the trial and other phases many concrete mixes were tried in the trial phase with the addition of fibers. The goal was to be able to determine a concrete mix where the fibers can be added and the workability would still be acceptable.

As for the instruments used and testing conditions, the cubes and cylinders were tested using the compression machine, FTS brand; while the beams were tested using the flexure testing machine, ELE brand, at a constant rate 0.2 mm/sec. All samples were cured at 100% humidity until the testing date. One day prior to testing, the samples were removed from the curing room, left to dry, and tested at dry condition and room temperature.

4.2.1. Cubes – Compression Samples

The cube samples with fibers described in Table 3.1 showed inconsistencies in some of test results obtained as they varied for the same control mix and between different fiber mixes, as illustrated in Table 4.1. The discrepancies could be attributed to relatively small cubes size (70 mm), and the presence of medium coarse aggregates (10 mm) in addition to the fibers in the concrete mix should have exacerbated the problem. Therefore, the cube results should be considered unreliable and practically disregarded, and the larger standard cylinders (150 x 300 mm) will be needed.

The results of the small cubes are still reported in this research which could serve as cautionary guidance to future researchers who may be interested to do similar or follow up on the current work.

4.2.2. Beams – Flexure Samples

The flexural load-deflection curves for the tested beams described in Table 3.2are shown in Figures 4.1, 4.2, 4.3, and 4.4, at 10 and 28 days concrete age.

Table 4.1. Compressive Strength for Cubes (7 cm) at 10 and 28 Days.

Mix No.	Mix Type	Compression Tests (kg/cm^2)	
		10 days	28 days
1	Control 1	226	233
2	Control 2	294	331
3	Control 3	310	359
4	1%Polypropylene	172	202
5	0.5%Steel	280	213
6	0.5% Hemp	164	211
7	0.5%Hemp-10%coarse	222	277
8	0.5%Hemp-20%coarse	176	173
9	0.75%Hemp	262	370
10	0.75%Hemp-20%coarse	275	350
11	1%Hemp-20%coarse	240	329
12	0.5%Local Hemp	268	380
13	0.5%-Palm	208	271
14	0.5%-Palm-10%coarse	199	256
15	0.5%-Palm-20%coarse	203	274
16	1%Palm	250	341
17	1%Banana	254	329

Table 4.2. Maximum Flexural Load and Correspondent Deflection for Beams (5 x 5 x 20 cm), at 10 and 28 Days.

		10 Days		28 Days	
Mix No.	**Mix Type**	**Maxi. Load (kN)**	**Deflection (mm)**	**Maxi. Load (kN)**	**Deflection (mm)**
1	Control	3.6	0.29	4.6	0.58
2	Control	3.3	0.71	4.6	0.99
3	Control	4.2	0.79	3.6	1.11
4	1%Polypropylene	3.9	0.82	3.4	0.65
5	0.5%Steel	4.9	0.61	4.7	0.37
6	0.5%Hemp	2.9	0.76	3.7	0.58
7	0.5%Hemp-10%coarse	2.6	0.51	3.7	0.85
8	0.5%Hemp-20%coarse	2.5	0.41	3.6	0.75
9	0.75%Hemp	3.5	0.81	6.5	0.71
10	0.75%Hemp-20%coarse	4.1	0.66	4.3	0.58
11	1%Hemp-20%coarse	3.6	0.84	3.6	0.75
12	0.5%Local Hemp	3.8	0.33	4.7	0.61
13	0.5%-Palm	3.2	0.41	3.9	0.52
14	0.5%-Palm-10%coarse	3.3	0.36	3.9	0.61
15	0.5%-Palm-20%coarse	3.6	0.38	3.7	0.22
16	1%Palm	3.8	0.73	4.4	1.37
17	1%Banana	4.6	0.98	3.6	0.43

The maximum flexural loads of all specimens are presented in Table 4.2. The results indicate that the use of fibers such as steel, polypropylene, and industrial hemp in concrete mixes has varying effects with respect to the flexural strength but obvious beneficial effects with regards to and providing a ductile post-cracking behavior of the fiber-reinforced concrete mix.

For mixes without coarse aggregate reduction, the concrete mix with 0.5% steel fibers resulted in a better flexural load as the control samples, with a post-cracking ductile behavior. Concrete mixes with 1% polypropylene fibers compared well with control samples at early age, while it was less at 28 days strength. The mix with 0.5% hemp showed a decrease compared to the control samples; whereas, when the hemp fibers were increased to 0.75%, the flexural strength compared well with the control samples at early age, and it exceeded the control samples at late strength. It is also worth mentioning, and similarly to the cube results, that the mix with 0.5% local hemp performed better than the other 0.5% hemp mixes and compared well with the control samples.

For mixes with coarse aggregate reduction, mixes with 0.5% hemp and a 10 or 20% coarse aggregate reduction are less than control samples by about 20% to 30% at 10 days and 28 days. Compared with control samples, the concrete mixes with 0.75% hemp and 20% coarse reduction were similar, at early and late age. The concrete mixes with 1% hemp and 20% coarse reduction compared well with the control mix at 10 days, while it was less by about 20% at 28 days.

Comparing hemp fiber mixes with steel and polypropylene mixes, it is clear that the steel mixes showed the best performance; whereas, mixes with polypropylene fibers compared well with those with hemp fibers. Note that the steel fibers are considered as rigid while all others are flexible.

The fiber-reinforced concrete behavior depends on the matrix and the fibers orientation, especially in the presence of coarse aggregate and small sample size. However, at 28 days, it was common with all fiber-reinforced mixes that the deflections correspondent to maximum flexural load ranged between 0.58 – 1.37 mm compared to 0.58 – 1.11 mm for control sample. The shift in the deflection is probably due to the presence of fibers and consequently the decrease in the stiffness of fiber-reinforced concrete mixes.

The fiber-reinforced concrete flexural behavior depends on the matrix and the fibers orientation, especially in the presence of coarse aggregates and small sample sizes. For fiber-reinforced concrete, the deflections at maximum flexural loads are larger than those of control samples; consequently decreasing the stiffness of fiber-reinforced concrete mixes.

No statistical performance was conducted in the trial phase for many reasons. Since the number of samples was not always similar, and the performed tests included only compression and flexure, in addition to having small samples relative to concrete mixes, as was the case with cubes results discrepancies.

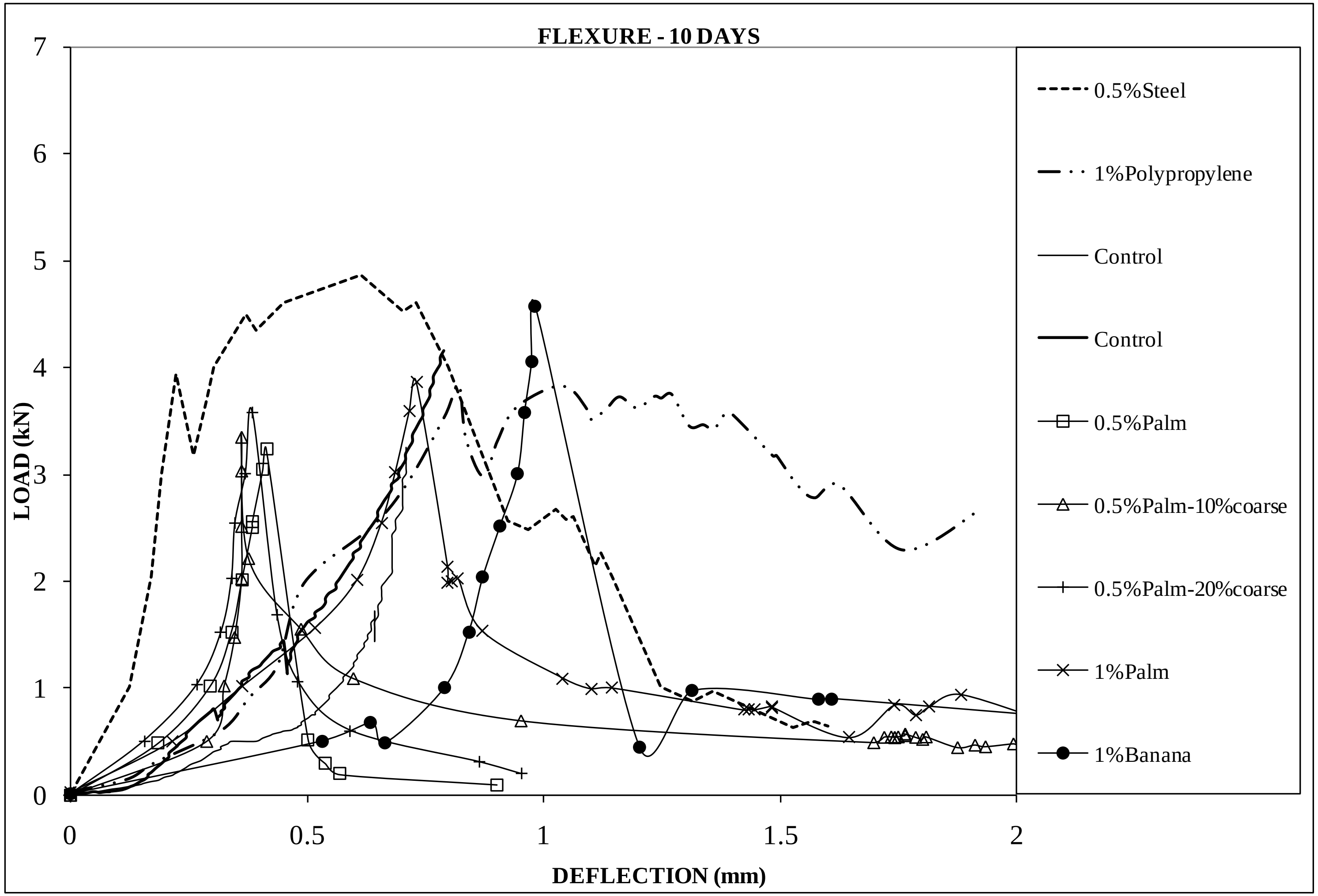


Figure 4.1. Flexural Load-Deflection Curves for Beams (5 x 5 x 20 cm), at 10 days. (Palm, Banana, Steel, Polypropylene Fibers, and Control Samples).

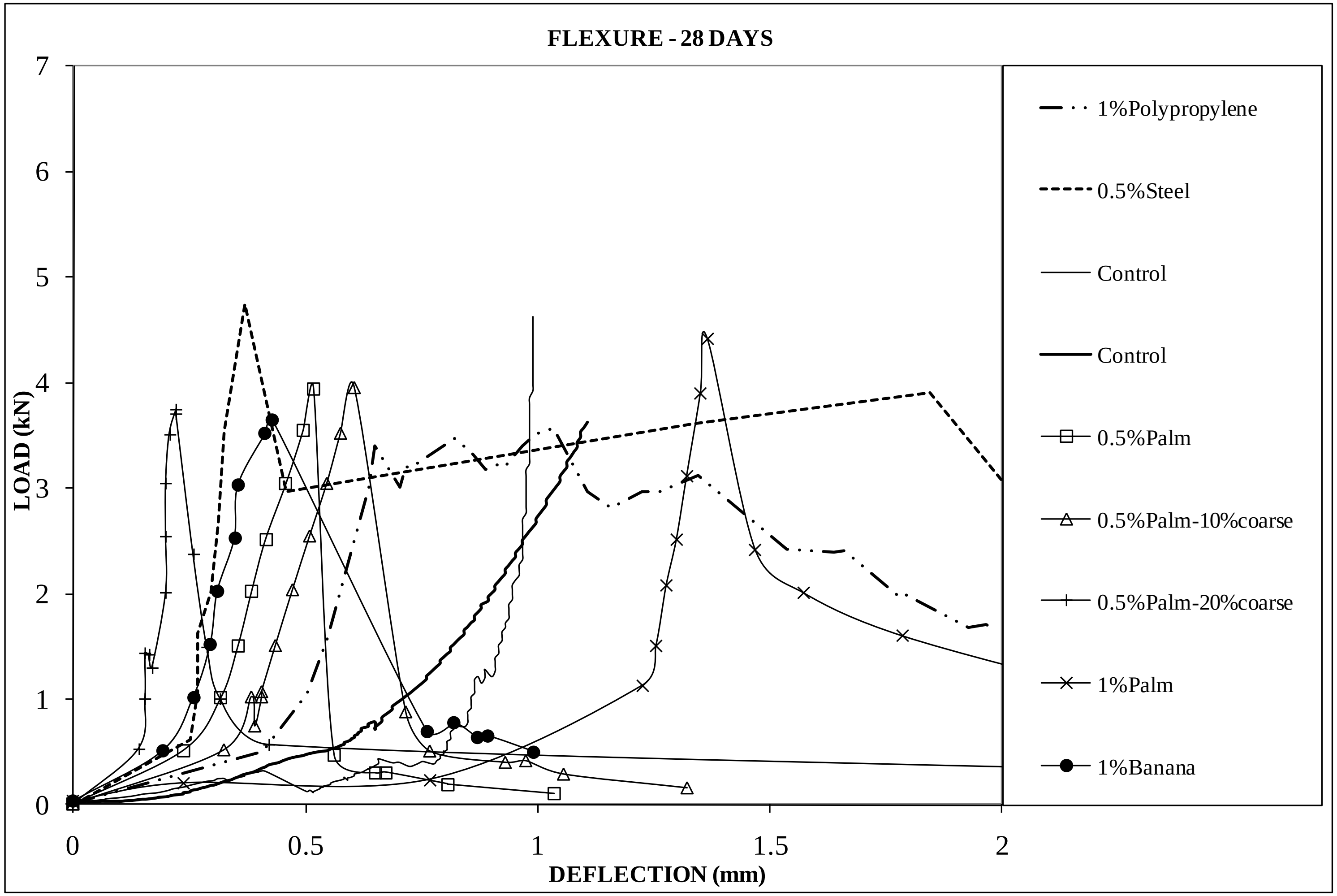


Figure 4.2. Flexural Load-Deflection Curves for Beams (5 x 5 x 20 cm), at 28 days. (Palm, Banana, Steel, Polypropylene Fibers, and Control Samples).

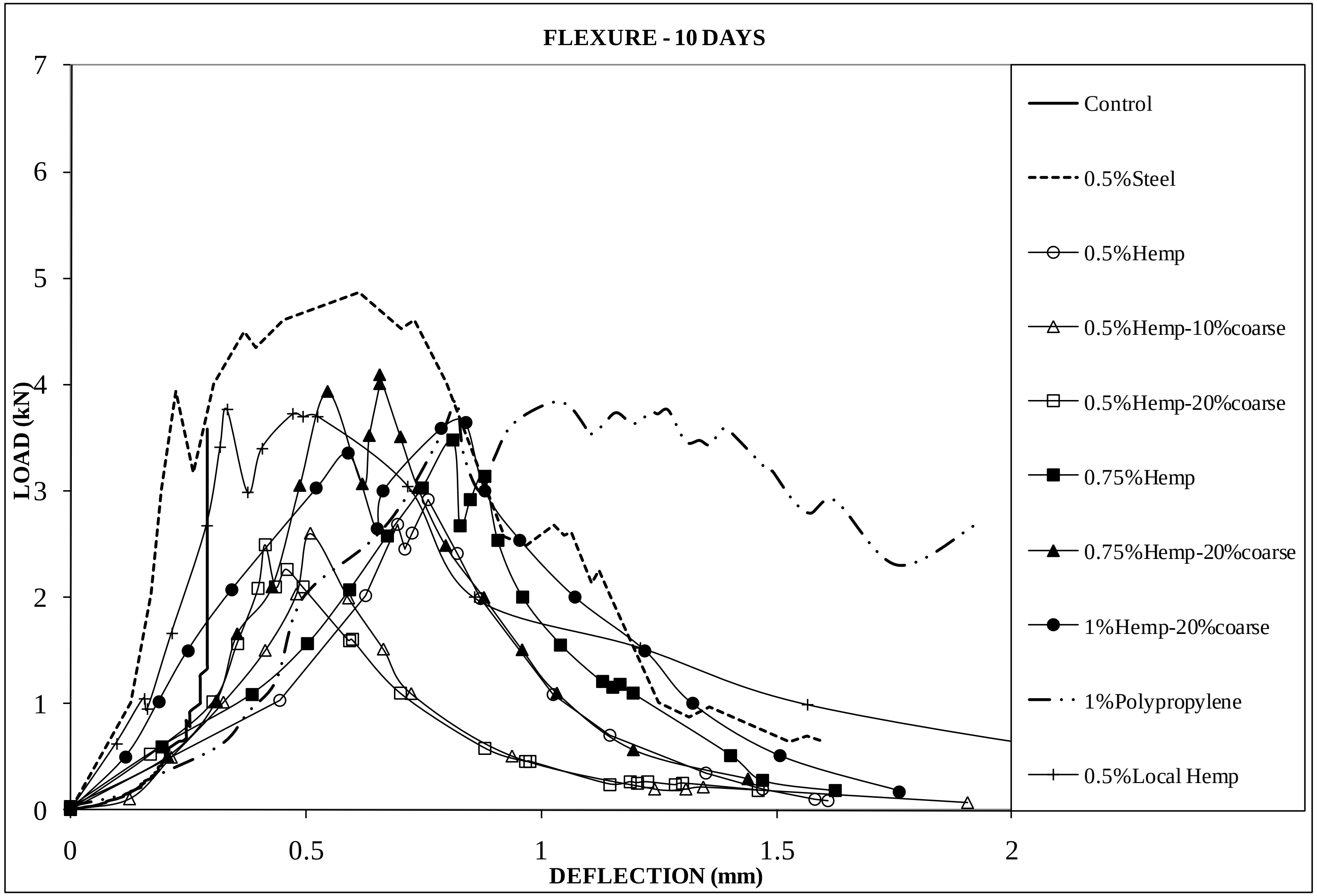


Figure 4.3. Flexural Load-Deflection Curves for Beams (5 x 5 x 20 cm), at 10 days. (Hemp, Steel, Polypropylene Fibers, and Control Samples).

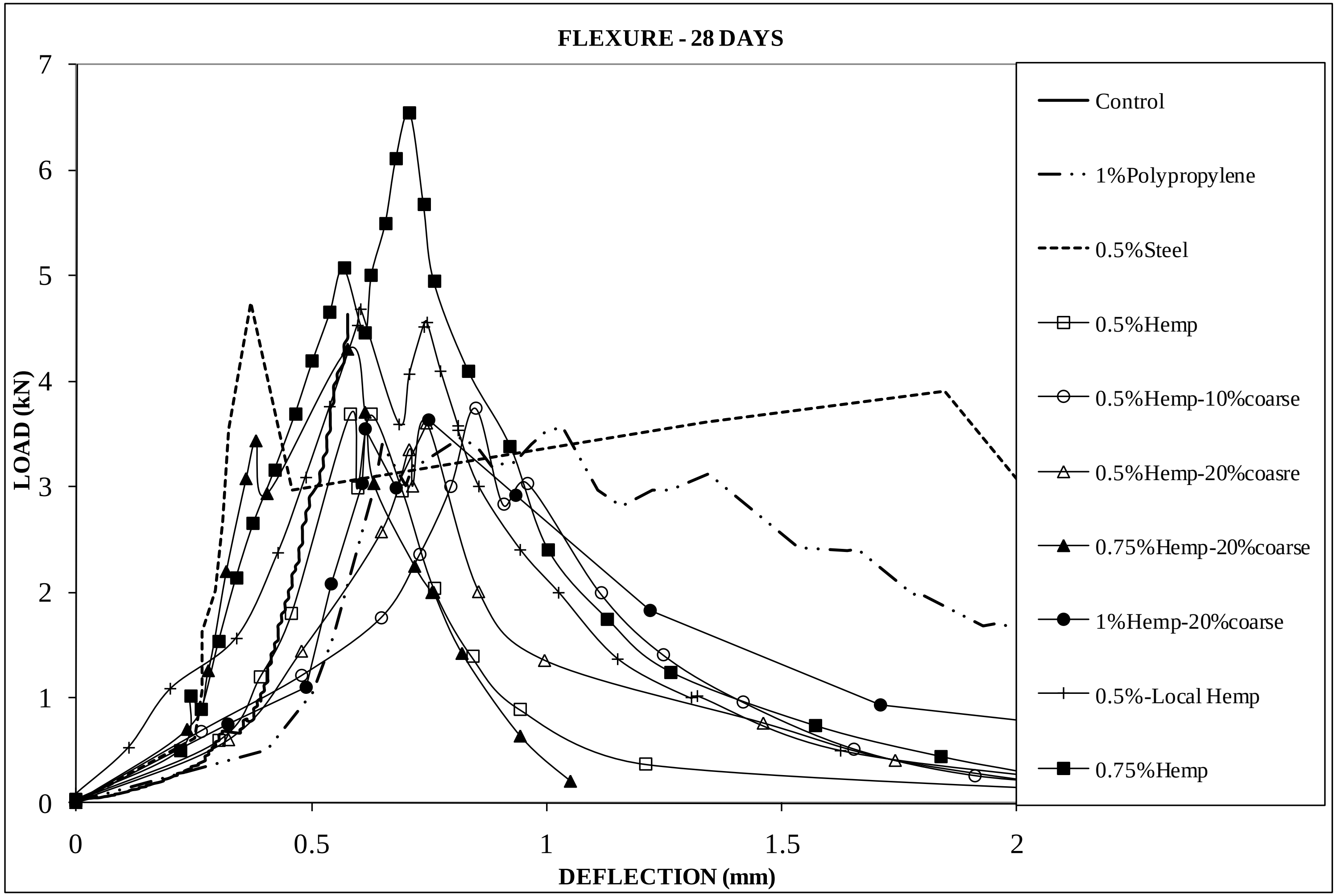


Figure 4.4. Flexural Load-Deflection Curves for Beams (5 x 5 x 20 cm), at 28 days. (Hemp, Steel, Polypropylene Fibers, and Control Samples).

4.3. Summary and Conclusion

In the trial mixes phase, many concrete mixes were tried with and without fibers. The aim was to determine a unique concrete mix and adopt in the research. The fibers tested in this phase are steel, polypropylene, banana, palm, and industrial hemp. Control mixes, without fibers, were included for comparison purposes, in addition to the mixes with the synthetic fibers steel and polypropylene. The monitoring tests are small compression cubes and flexure beams.

Based on the test results of this trial phase, the fibers presence affected both compression and flexural strengths. However, the variation in the strength is affected by the fibers type and volumetric fraction, and possibly the small sample sizes. Comparing between different fibers, steel fibers showed the best results. Polypropylene and the agricultural fibers showed similar results with some variations. Between the agricultural fibers, the hemp has showed the best post-ductile behavior.

In the following phase one, the steel, banana, and palm fibers will be excluded. The research will proceed with polypropylene and hemp fibers mixes in addition to control mixes. In this phase, a full large-scale research testing set will be provided and presented in chapter 5.

CHAPTER 5

PHASE ONE RESULTS AND STATISTICAL ANALYSIS

5.1. Introduction

In the trial phase presented in chapter 4, many trial mixes have been prepared and investigated, and consequently the possible volume fractions of fibers were determined in addition to the coarse aggregate reduction. The hemp fibers were selected for further investigation in phase one, in addition to the polypropylene fiber mix and control mix for comparison purposes. The banana and palm fibers are not included, since the hemp fibers performed better in the trial mixes and due to practical and availability of large fibers quantity. The maximum possible fibers volume fraction is 1%, while the mix can still be workable. Also, a coarse aggregate reduction up to 30% by concrete volume is needed to allow for enough mortar matrix for the fibers to interact within. Thus, in the first phase, three hemp fibers volume fractions are considered: 0.5%, 0.75%, and 1% in addition to three coarse aggregate reductions by concrete volume: 0% (no reduction), 10%, 20%, and 30%. In this phase, a full scale of tests was adopted in order to provide adequate and enough testing data for the analysis of the new material investigated. The tests considered are compressive strength, flexure, splitting tensile, modulus of elasticity, thermal conductivity, density, and slump tests.

In order to validate the tests data of this phase, the use of statistical analysis methods is included. The main data sufficient for statistical data analysis are from phase 1, since many tests were performed and the number of specimens was as the minimum required for representation, i.e. three specimens per test. The Statistical

Analysis System (SAS, 2008) was used for data analysis. Data were statistically analyzed as one way ANOVA (Analysis of Variance) using the GLM (General Linear Model) procedure of SAS and the different means were compared to the control using Dunnett's method; in addition, data on hemp concrete with coarse reduction were analyzed by the two-way ANOVA of SAS (2008) and mean comparison was performed using Duncan's Multiple Range test where appropriate.

Analytical linear models are also included, in order to predict the results of the compressive strength, modulus of elasticity, and flexure tests at 28 days concrete age. The input data for the models are based on the correspondent control tests results. The variables considered in the linear models are the fibers volume fraction, coarse aggregate reduction, and the fibers aspect ratio.

5.2. Phase One Test Results

As detailed in chapter 3 (section 3.3.2), a total of 180 cylinders, 72 beams, and 12 blocks were prepared in phase 1. The compressive strength was determined at 3, 7, and 28 days concrete age. The flexural strength was determined at 7 and 28 days. All other tests were performed at 28 days. Note that, for a best data representation, all reported test results, except thermal block test, are the average of three tested specimens. For the thermal block test, one specimen was enough, since the thermal test determines the average thermal conductivity along the specimen surface.

5.2.1. Compressive Strength Test Results – ASTM C39

Using standard cylinders (15 x 30 cm), the compressive strength was determined at 3, 7, and 28 days. The results are presented in Table 5.1 and illustrated in Figure 5.1, with comparison to the control mix specimens results. As expected, and due to dimensions difference and specimens representative number (3 specimens per test), the average compressive strength results of standard cylinders are more consistent than those of the cubes results in the trial phase. The results indicate that the cylinder tests, prepared with different fibers volumetric ratios and reductions in coarse aggregate, result in a decrease in the compressive strength with the increase in coarse aggregate reduction.

For mixes without coarse aggregate reduction, and compared to the control specimens, the compressive strength in the 0.5% polypropylene mix decreased by 3 to 17%, at 3 to 28 days. The compressive strength in the 0.5% hemp mix decreased by about 20% at 7 and 28 days, with an exception at 3 days. Comparing the 0.5% polypropylene mix with 0.5% hemp mix, the compressive strength results were similar. For mixes with coarse aggregate reduction, and compared with the control specimens, the compressive strength generally decreased as the coarse aggregate reduction is increased. The 0.5%, 0.75%, and 1% hemp mixes decreased by about 20 to 40%, 15 to 40%, and 20 to 35% at different concrete ages, respectively.

At 28 days concrete age, the 0.5%, 0.75%, and 1% hemp mixes, with 10%, 20%, and 30% coarse aggregate reduction, varied between 17.5 to 20 MPa, respectively, compared to 23.4 MPa for the control specimen. For most hemp mixes with coarse aggregate reduction, the decrease of strength at 28 days was the same or close to that at 3 days.

Table 5.1. Standard Cylinders (15 x 30 cm) Compressive Strength Average Test Results at 3, 7, and 28 Days.

Mix No.	Mix Type	3 Days		7 Days		28 Days	
		MPa	Difference to Control	MPa	Difference to Control	MPa	Difference to Control
1	Control	11.9	-	19.4	-	23.4	-
2	0.5%Polypropylene	11.5	-3%	16.1	-17%	20.4	-13%
3	0.5%Hemp	12.8	+8%	15.6	-20%	18.9	-19%
4	0.5%Hemp-10%coarse	9.8	-17%	14.3	-26%	17.5	-25%
5	0.5%Hemp-20%coarse	8.9	-25%	12.6	-35%	16.7	-29%
6	0.5%Hemp-30%coarse	8.3	-30%	11.4	-41%	17.8	-24%
7	0.75%Hemp-10%coarse	10.2	-14%	12.7	-34%	20.1	-14%
8	0.75%Hemp-20%coarse	8.7	-26%	12.2	-37%	17.1	-27%
9	0.75%Hemp-30%coarse	7.6	-36%	11.9	-39%	17.9	-23%
10	1.0%Hemp-10%coarse	9.1	-23%	12.6	-35%	18.9	-19%
11	1.0%Hemp-20%coarse	9.4	-21%	13.4	-31%	18.2	-22%
12	1.0%Hemp-30%coarse	9.6	-19%	14.0	-28%	16.8	-28%

Table 5.2. Modulus of Rupture Results, Based on Flexural Beam Tests, at 7 and 28 Days.

Mix No.	Mix Type	7 days		28 days	
		MOR (MPa)	% difference to Control	MOR (MPa)	% difference to Control
1	Control	2.6	-	3.4	-
2	0.5%Polypropylene	2.6	+1%	2.6	-24%
3	0.5%Hemp	2.3	-9%	2.3	-31%
4	0.5%Hemp-10%coarse	2.2	-16%	2.9	-14%
5	0.5%Hemp-20%coarse	2.1	-18%	2.7	-19%
6	0.5%Hemp-30%coarse	2.2	-13%	2.7	-21%
7	0.75%Hemp-10%coarse	2.6	+1%	3.1	-7%
8	0.75%Hemp-20%coarse	2.2	-12%	2.6	-24%
9	0.75%Hemp-30%coarse	2.4	-8%	2.5	-27%
10	1%Hemp-10%coarse	2.3	-12%	1.5	-57%
11	1%Hemp-20%coarse	2.3	-8%	1.9	-45%
12	1%Hemp-30%coarse	2.9	+14%	3.0	-11%

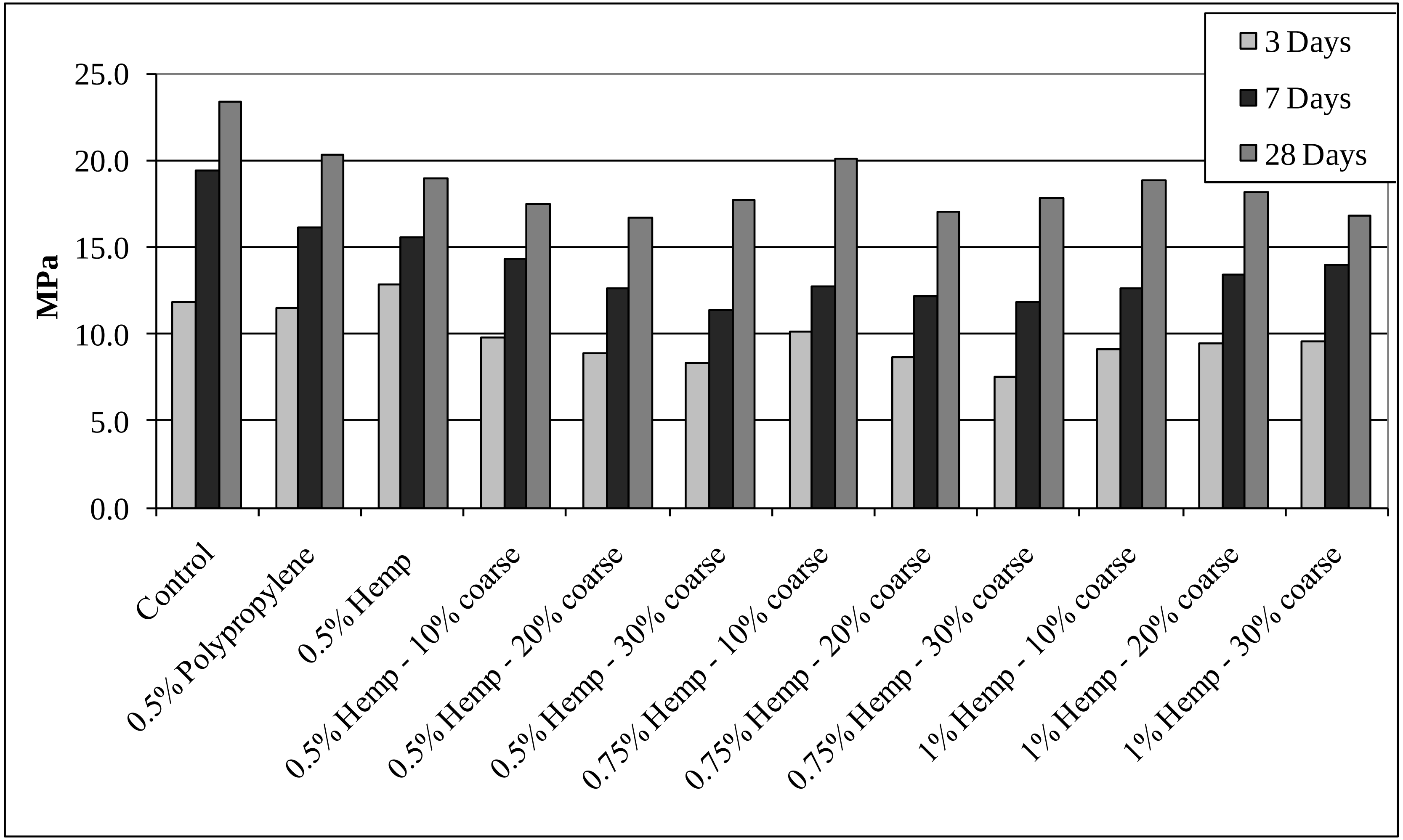


Figure 5.1. Plot of Cylinders Compressive Strength Test Results at 3, 7, and 28 Days.

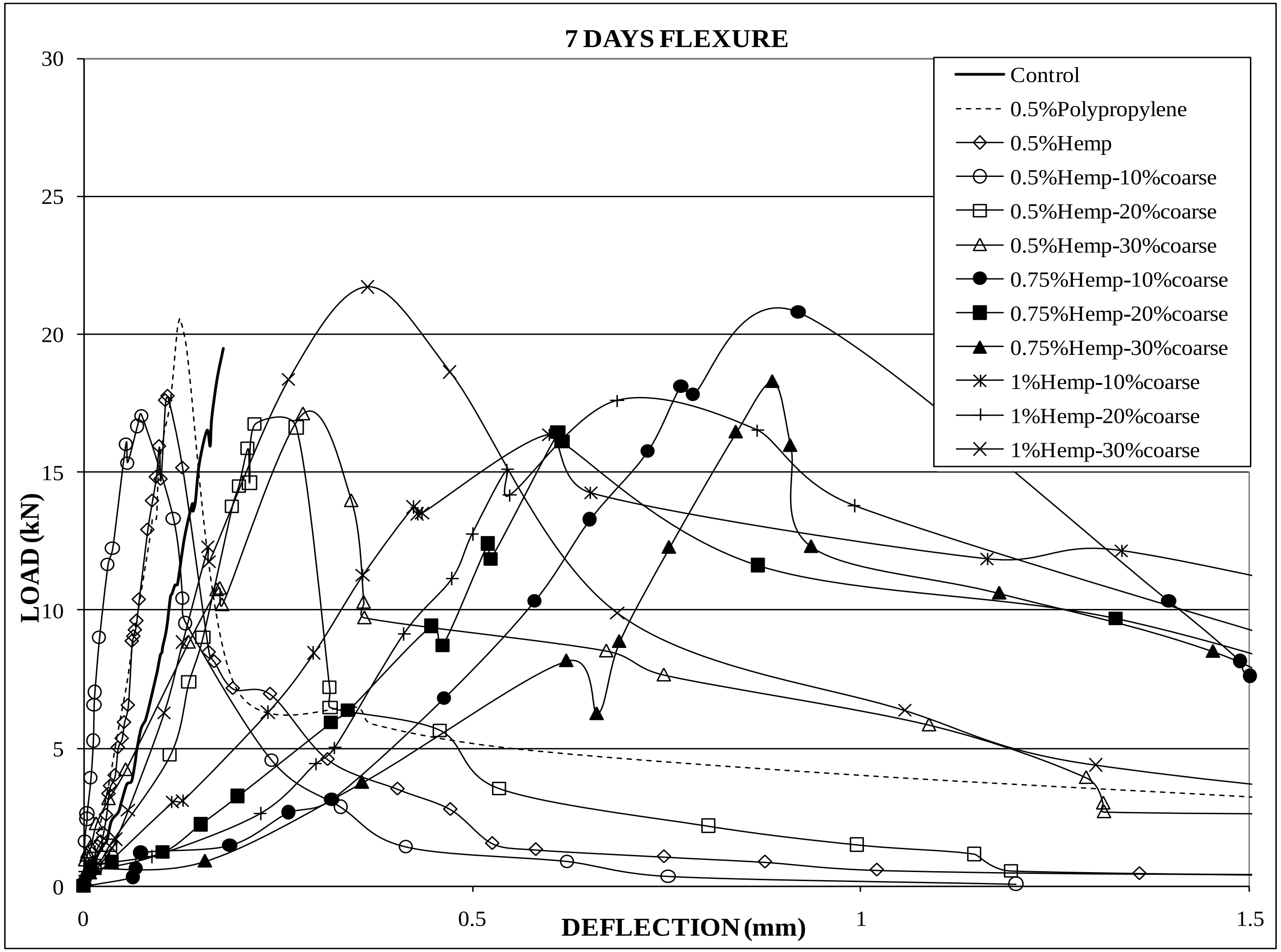


Figure 5.2. Flexural Load-Deflection Curves for Beams (15 x 15 x 53 cm) Tested at 7 Days.

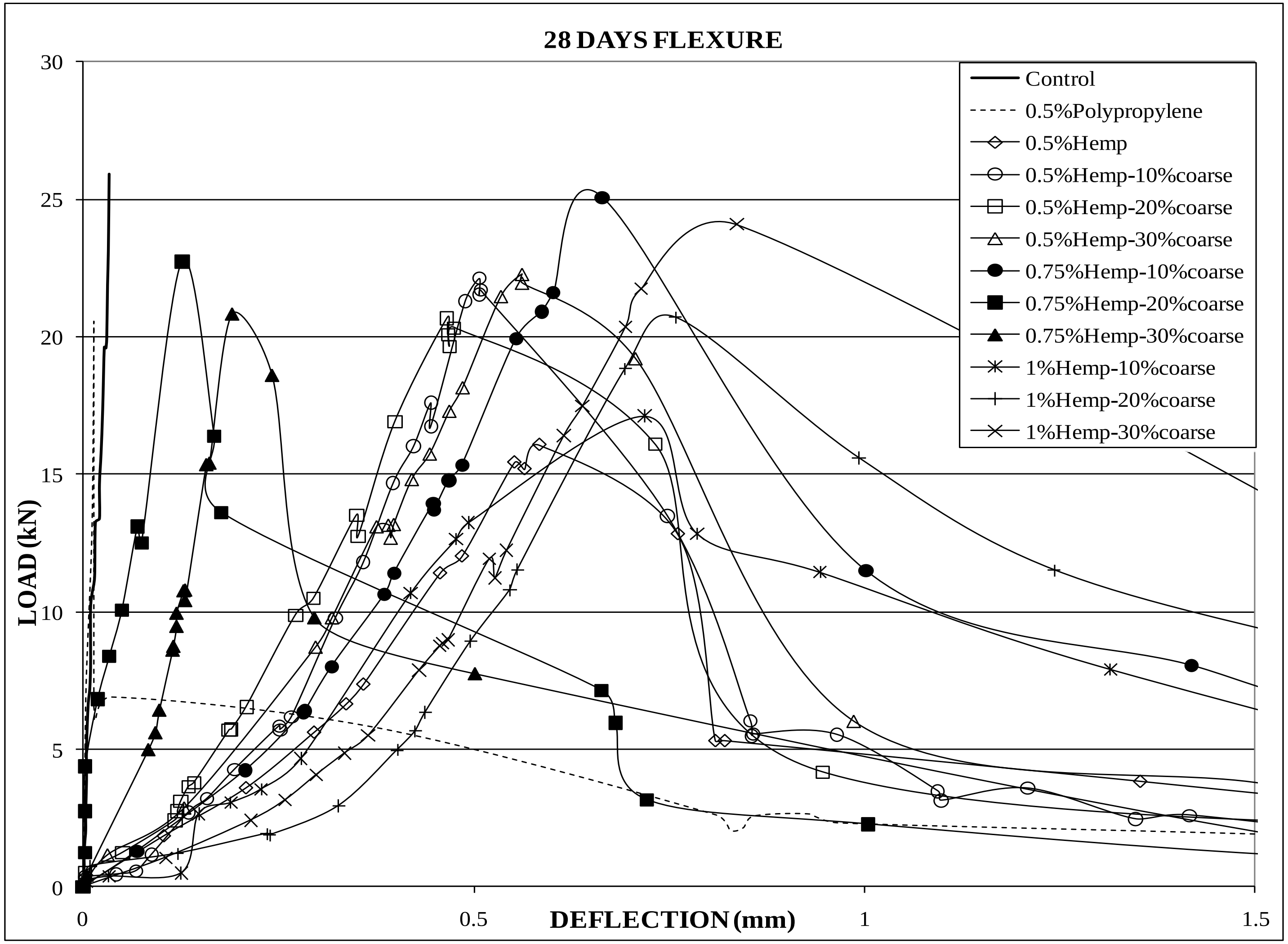


Figure 5.3. Flexural Load-Deflection Curves for Beams (15 x 15 x 53 cm) Tested at 28 Days.

In general, the compressive strength of fiber-reinforced concrete mixes tends to decrease in the presence of fibers.

5.2.2. Flexure Beam Test – ASTM C78

Beam specimens (15 x 15 x 53 cm) were used to determine the load-deflection curves of different concrete mixes.

The flexure beam test was performed at 7 and 28 days of concrete age, in order to monitor the different mixes performance at early and late concrete strength. Figures 5.2 and 5.3 show the flexure beam test results at 7 and 28 days, respectively. It is worth noting that the flexure beam results may vary with different beam replicates for the same mix due to the fibers orientation and distribution in the beam specimens. Consequently, the load-deflection curves variations may be expected.

Based on the load-deflection curves, the modulus of rupture (MOR) was also determined. According to ASTM C78, and assuming that the fracture initiates within the middle third of the beam length: $MOR = PL/bd^2$, where P(kN) is the peak machine load reached, b is the beam width (150 mm), d is the beam depth (150 mm), and L is the beam clear length within supports (450 mm). Table 5.2 summarizes the MOR results at 7 and 28 days.

For mixes without coarse aggregate reduction, the 0.5% hemp and 0.5% polypropylene mixes MOR results were almost the same. At 7 days, the MOR results were close to that of the control specimen. At 28 days, the results were less by about 25 to 30% than control specimen.

For mixes with coarse aggregate reduction, at 7 days, almost all mixes MOR results were less than control mix MOR by about 10-15%; whereas, at 28 days, the variation from the control specimen was about 15-25% with some exceptions, as low as 10% and as high as 50%

As for the load-deflection curves (Figure 5.2 and 5.3), the benefits of the fiber-reinforced concrete compared to plain concrete are illustrated. Although the MOR of most mixes is less than that of control mix, the ductile behavior after the maximum load is reached, i.e. the post-crack behavior, is of major importance because it modifies the concrete mode of failure from brittle to ductile. The load-deflection curves results illustrate the ductile behavior of the fiber-reinforced concrete composite after the peak load is reached. The ductile behavior is directly related to the toughness of the composite material. The control specimen results show the brittle failure of plain concrete after the peak load is reached. For example, with 0.75% hemp and 20% coarse reduction and similarly with 1% hemp and 30% coarse reduction, the peak load is almost the same as that of the control specimen, while the toughness increases as simulated by a larger area or more energy absorption under the load-deflection curves. This explains the ductility of the new composite while keeping the same flexural strength as plain concrete. Note that other hemp and coarse aggregate percentages show a ductile behavior but not to the same extent.

5.2.3. Splitting Tensile Test – ASTM C496

Standard cylinders (15 x 30 cm) were tested at 28 days, under a splitting tensile load until failure. The average of three specimens is considered for every test. The splitting tensile test results are presented in Table 5.3 and illustrated in Figure 5.4, with comparison to the control mix results.

For the splitting tensile strength, all hemp mixes performed better than the polypropylene mix. For the 0.75% hemp mixes with 20 and 30% coarse reduction, and all 1% mixes, the splitting tensile results were almost the same as the control mix. Only the 0.5% hemp mixes, 0.5% polypropylene, and 0.75% hemp with 10% coarse reduction mixes showed a decrease of about 20-30%.

The results indicate that the 0.75% and 1% hemp volume fractions are sufficient and adequate as an optimal substitute to the coarse reduction. Note that the splitting tensile strength results agree with the ASTM specifications, i.e. they are generally less than the MOR results. Further, and as would be expected, the splitting tensile strength results are about 10% of the compressive strength results, for plain concrete. However, it is not always the case for fiber-reinforced concrete.

5.2.4. Modulus of Elasticity Test – ASTM C469

The modulus of elasticity was measured, according to ASTM C469, for all mixes. The modulus also was calculated using concrete density and compressive strength equation. Both measured and calculated modulii are compared, in addition to comparing the measured values of different mixes, with that of the control mix. All results are presented in Table 5.4 and illustrated in Figure 5.5.

The new composite is more ductile and thus with less stiffness (i.e. larger deflection at same load) as was observed in Figures 5.2 and 5.3. As presented in Table 5.4, all measured hemp specimen results were less than the measured control specimens, even with 0.5% hemp with no reduction, which justifies the role of fibers when added to plain concrete in reducing the stiffness and increasing the ductile behavior.

The modulus of elasticity of hemp mixes showed a decrease of about 20-30% compared to the control mix. These results are consistent with the load-deflection curves, where they are shifted to the right, i.e. reduced stiffness. Besides, some differences, mainly with 0.5 and 0.75% hemp mixes, appeared between the measured and calculated modulii. Many factors can be attributed to such differences like the concrete density and compressive strength. However, in most mixes both the measured and calculated modulii did agree, which reinforce the difference to the control mix results in both cases.

5.2.5. Thermal Conductivity Block Test – ASTM C518

The thermal conductivity of the concrete mixes was determined according to ASTM C518. For every mix, one block (5 x 30 x 30 cm) was tested and an average value was reported, as presented in Table 5.5 and illustrated in Figure 5.6. Most 0.75% and all 1% Hemp mixes with coarse reduction showed a thermal conductivity less than the control mix up to 35%. This test shows that the presence of sufficient hemp fibers would substantially improve the thermal properties of concrete mixes, resulting in an insulating concrete.

5.2.6. Density Test – ASTM C642

The density of hardened concrete was determined and all mixes results are presented in Table 5.6 an illustrated in Figure 5.7. The density results are compared to that of the control mix. As expected, the densities of hemp mixes with aggregate reduction were less by about 3-7%.

Table 5.3. Splitting Tensile Strength, Cylinders (15 x 30 cm) Results, at 28 Days.

Mix No.	Mix Type	28 days	
		MPa	% difference to Control
1	Control	2.3	-
2	0.5%Polypropylene	1.8	-21%
3	0.5%Hemp	2.2	-1%
4	0.5%Hemp-10%coarse	1.9	-14%
5	0.5%Hemp-20%coarse	1.6	-27%
6	0.5%Hemp-30%coarse	1.6	-29%
7	0.75%Hemp-10%coarse	1.8	-20%
8	0.75%Hemp-20%coarse	2.2	-3%
9	0.75%Hemp-30%coarse	2.1	-5%
10	1%Hemp-10%coarse	2.2	-1%
11	1%Hemp-20%coarse	2.2	-4%
12	1%Hemp-30%coarse	2.3	+1%

Table 5.4. Modulus of Elasticity Test Results, at 28 Days.

Mix No.	Mix Type	28 days			
		$E_{measured}$ (kg/cm^2)	*$E_{calculated}$ (kg/cm^2)	% difference $E_{measured}$ to $E_{calculated}$	% difference to Control (E_m)
1	Control	237,536	223,353	+6%	-
2	0.5%Polypropylene	218,184	204,162	+7%	-8%
3	0.5%Hemp	220,035	199,232	+10%	-7%
4	0.5%Hemp-10%coarse	189,350	185,007	+2%	-20%
5	0.5%Hemp-20%coarse	173,040	178,878	-3%	-27%
6	0.5%Hemp-30%coarse	215,426	178,124	+21%	-9%
7	0.75%Hemp-10%coarse	149,196	198,472	-25%	-37%
8	0.75%Hemp-20%coarse	206,788	179,815	+15%	-13%
9	0.75%Hemp-30%coarse	161,341	183,973	-12%	-32%
10	1%Hemp-10%coarse	189,662	190,353	0%	-20%
11	1%Hemp-20%coarse	169,598	181,923	-7%	-29%
12	1%Hemp-30%coarse	170,883	168,933	+1%	-28%

**Ecalculated = 33.w3/2.sqrt(f'c) ,where w = unit weight in (lb/cu.ft) and f'c = compressive strength in (psi)*

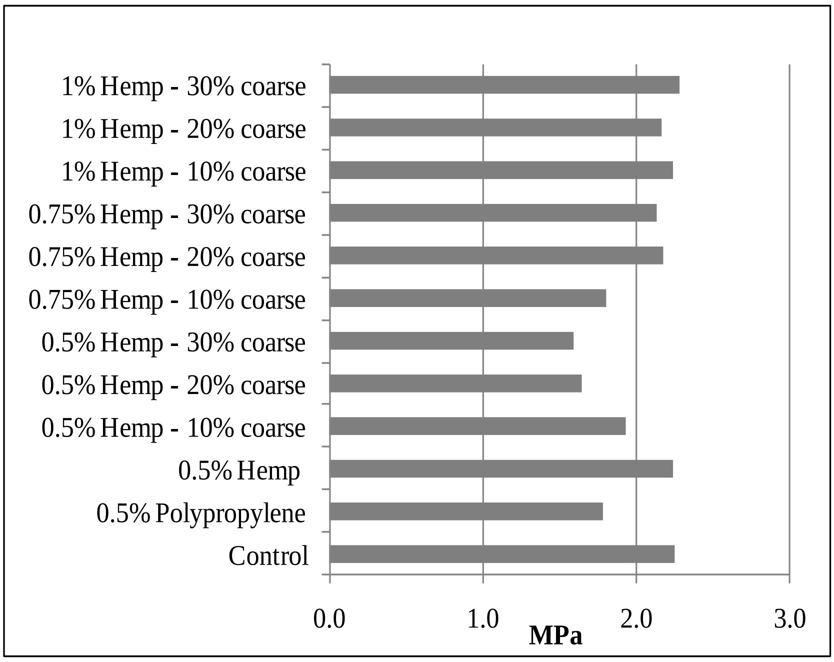


Figure 5.4. Plot of Splitting Tensile Test Results.

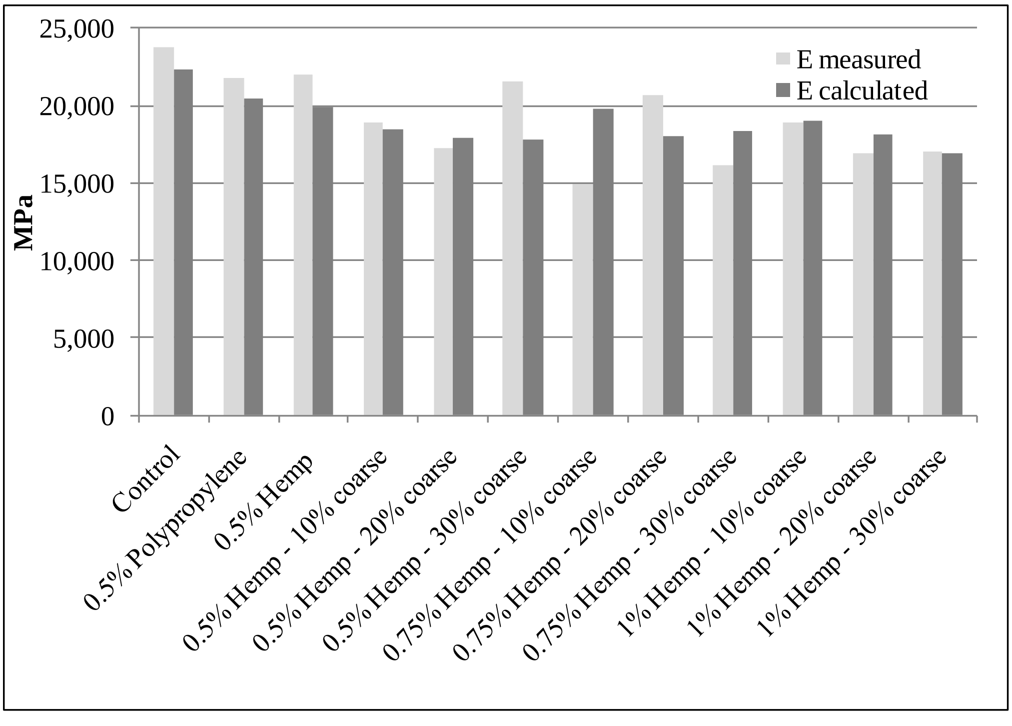


Figure 5.5. Plot of the Modulus of Elasticity Test Results.

Table 5.5. Thermal Conductivity Results on Block (5 x 30 x 30 cm), at 28 Days.

Mix No.	Mix Type	28 days	
		λ (Watt/meter. kelvin)	% difference to Control
1	Control	1.885	-
2	0.5%Polypropylene	1.608	-15%
3	0.5%Hemp	1.866	-1%
4	0.5%Hemp-10%coarse	1.504	-20%
5	0.5%Hemp-20%coarse	1.912	+1%
6	0.5%Hemp-30%coarse	1.661	-12%
7	0.75%Hemp-10%coarse	1.746	-7%
8	0.75%Hemp-20%coarse	1.418	-25%
9	0.75%Hemp-30%coarse	1.221	-35%
10	1%Hemp-10%coarse	1.226	-35%
11	1%Hemp-20%coarse	1.232	-35%
12	1%Hemp-30%coarse	1.414	-25%

Table 5.6. Density Test Results, at 28 Days.

Mix No.	Mix Type	Density (kg/m^3)	% difference to Control
1	Control	2,254	-
2	0.5%Polypropylene	2,223	-1%
3	0.5%Hemp	2,243	0%
4	0.5%Hemp-10%coarse	2,191	-3%
5	0.5%Hemp-20%coarse	2,176	-3%
6	0.5%Hemp-30%coarse	2,125	-6%
7	0.75%Hemp-10%coarse	2,192	-3%
8	0.75%Hemp-20%coarse	2,166	-4%
9	0.75%Hemp-30%coarse	2,198	-2%
10	1%Hemp-10%coarse	2,176	-3%
11	1%Hemp-20%coarse	2,138	-5%
12	1%Hemp-30%coarse	2,090	-7%

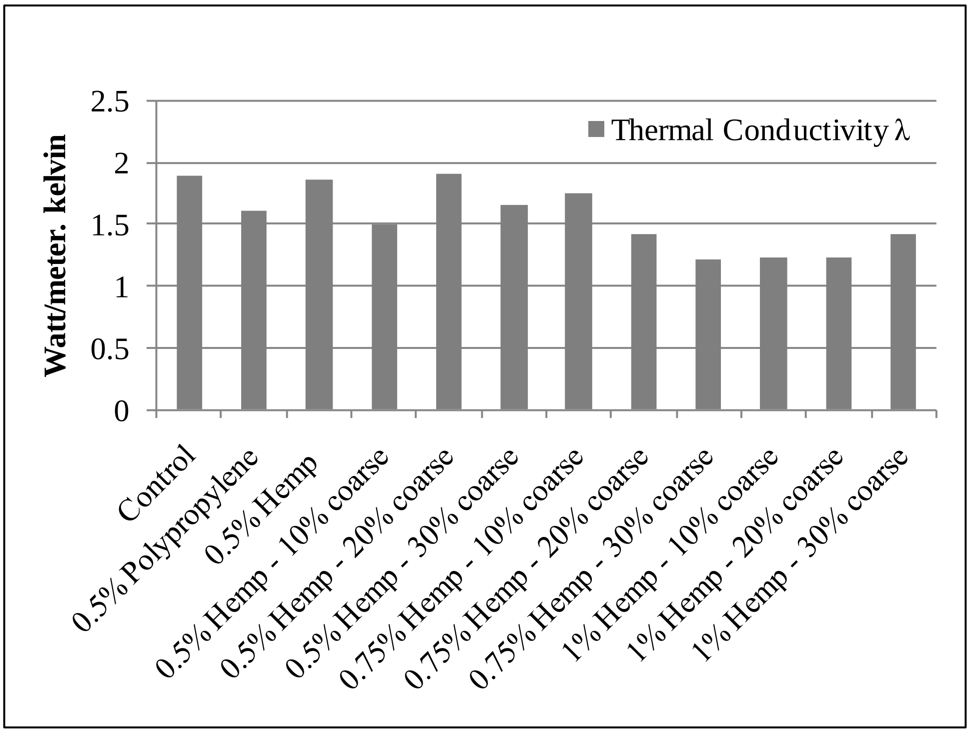


Figure 5.6. Plot of the Thermal Conductivity Test Results.

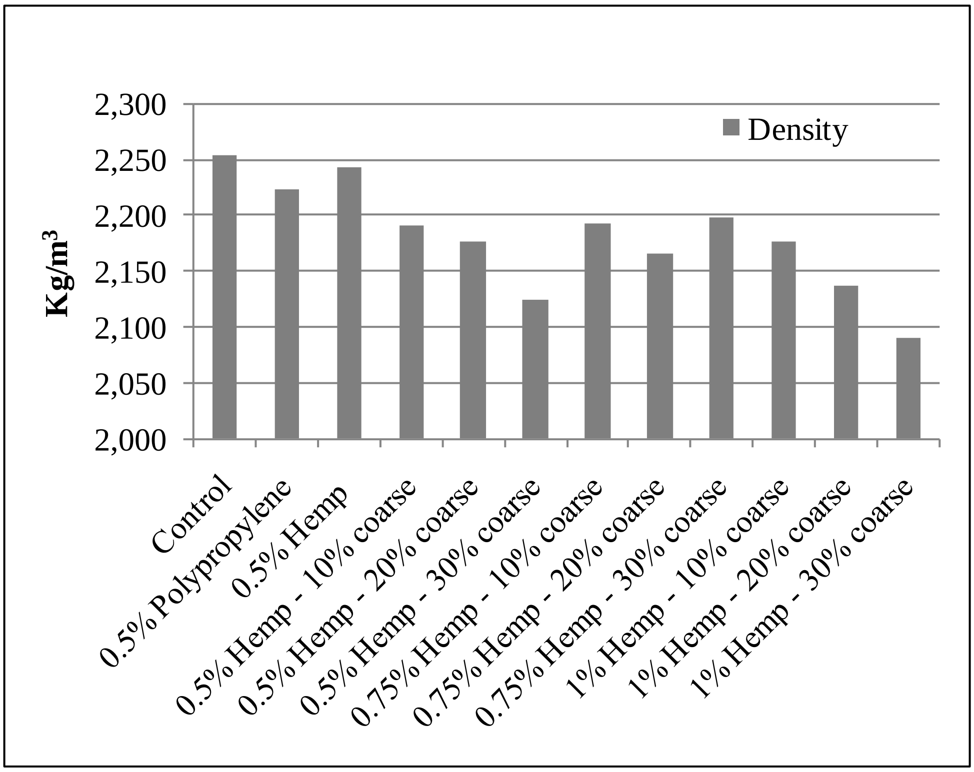


Figure 5.7. Plot of the Density Test Results.

Table 5.7. Slump Test Results.

Mix No.	Mix Type	Slump (cm)
1	Control	25
2	0.5%Polypropylene	22
3	0.5%Hemp	7
4	0.5%Hemp-10%coarse	11
5	0.5%Hemp-20%coarse	14
6	0.5%Hemp-30%coarse	17.5
7	0.75%Hemp-10%coarse	6.5
8	0.75%Hemp-20%coarse	11
9	0.75%Hemp-30%coarse	14
10	1%Hemp-10%coarse	7
11	1%Hemp-20%coarse	7
12	1%Hemp-30%coarse	7

The decrease in density is associated with the reduction in coarse aggregates but was not extensive.

5.2.7. Slump Test – ASTM C143

The slump test was performed on all mixes at the fresh state, while the concrete mixes were cast. Table 5.7 presents the slump test values. Mixes with 0.75% hemp and 20-30% coarse reduction showed an acceptable slump about 13 cm. The slump of 1% hemp mixes was close to the minimum allowable, resulting in a very stiff mix. The hemp fibers' high water absorption, the addition of these fibers to concrete resulted in reducing the slump of the composite mix. This is further confirmed by the fact that polypropylene addition did not affect the slump result since it does not absorb water. It is also evident that when the 1% hemp is added the workability of the mix decreased to a large extent and therefore going beyond the 1% hemp fibers is not recommended.

5.3. Statistical Analysis of Phase 1 Specimens

The tests data of phase 1 constituted sufficient sampling data for statistical analysis. All the data used in the statistical analysis are the average values of three specimens, as mentioned earlier. The analyzed data were of the following tests: compression tests (cylinders 15 x 30 cm) at 3, 7, and 28 days; flexure beam (15 x 15 x 53 cm) tests in term of the modulus of rupture (MOR), at 7 and 28 days; splitting tensile tests for cylinders (15 x 30 cm) at 28 days; and modulus of elasticity tests for cylinders 15 x 30 cm, at 28 days.

All data are analyzed based on 95% confidence level. One-way and two-way Analysis of Variance (ANOVA) are considered. The Dunnett's method for one-way ANOVA is used to compare all data with control mix data. The Duncan's method for two-way ANOVA is used to compare the data of all hemp mixes only, with different hemp fibers fractions, and different coarse aggregate reduction.

Table 5.8. One-Way ANOVA Results, Comparing All Tests Results with the Control Test Results.

Mix Type	Compression (MPa)			MOR (MPa)		Splitting (MPa)	Modulus (MPa)
	3d	**7d**	**28d**	**7d**	**28d**	**28d**	**28d**
Control	11.9	19.4	23.4	2.6	3.4	2.3	23,754
0.5%Polypropylene	11.5	16.1*	20.4*	2.6	2.6*	1.8*	21,818*
0.5%Hemp	12.9*	15.6*	18.9*	2.3	2.3*	2.2	22,004
0.5%Hemp-10%coarse	9.8*	14.3*	17.5*	2.2*	2.9	1.9*	18,935*
0.5%Hemp-20%coarse	8.9*	12.6*	16.7*	2.1*	2.7*	1.6*	17,304*
0.5%Hemp-30%coarse	8.3*	11.4*	17.8*	2.2*	2.7*	1.6*	21,543*
0.75%Hemp-10%coarse	10.2*	12.7*	20.1*	2.6	3.1	1.8*	14,920*
0.75%Hemp-20%coarse	8.7*	12.2*	17.1*	2.3	2.6*	2.2	20,679*
0.75%Hemp-30%coarse	7.6*	11.9*	17.9*	2.4	2.5*	2.1	16,134*
1%Hemp-10%coarse	9.1*	12.6*	18.9*	2.3	2.2*	2.2	18,966*
1%Hemp-20%coarse	9.4*	13.4*	18.2*	2.4	2.8*	2.2	16,960*
1%Hemp-30%coarse	9.6*	14.0*	16.8*	2.9*	3.0	2.3	17,088*
SEM*	***0.21***	***0.45***	***0.66***	***0.08***	***0.13***	***0.035***	***457.47***
* Significantly different from the Control result, and **SEM is the Standard Error of Mean.							

5.3.1. One-Way ANOVA Results

The tests data were analyzed using the general linear models procedure for one-way ANOVA, and means of all mixes were compared to the control mix by Dunnett's T- tests at a significant level of 0.05

As summarized and presented in Table 5.8, the different eleven mixes are compared to the control mix results as follows:

- The compressive strength results of all fiber mixes are significantly less and different, except for polypropylene mix at 3 days.
- For the flexure results, in terms of MOR, at 7 days only the 0.5% hemp mixes are significantly less; whereas, the 1.0% hemp-30% coarse mix is significantly larger. At 28 days, most mixes are significantly less except 0.5% hemp-10% coarse, 0.75% hemp-10% coarse, and 1.0% hemp-30% coarse mixes.
- Most of the splitting tensile test results are not significantly different and can be considered the same as control results; except the polypropylene, all 0.5% hemp with coarse reduction, and 0.75% hemp-10% coarse reduction.
- Finally, for the modulus of elasticity results, all mixes were significantly less than the control result, except the 0.5% hemp with no reduction.

Therefore, the one-way ANOVA statistical analysis with 95% confidence assures that the compressive strength and the modulus of elasticity tests results are significantly less than the control results; whereas, the tensile strength are not all significantly different. This indicates that the hemp mixes may have less compressive strength and are more flexible with lower modulus, while the tensile strength may not be affected; besides, the mode of failure is ductile instead of brittle.

5.3.2. Two-Way ANOVA Results

The tests data were analyzed using the general linear model procedure for two-way ANOVA, and means of all hemp mixes were compared by Duncan's T- tests at a significant level of 0.05.

Only the hemp mixes are considered in the two-way ANOVA, where simultaneously two variables are of concern, the fibers volume fraction and the coarse aggregate reduction. In this method, the included results are for the compressive strength tests at 3, 7, and 28 days, the modulus of rupture at 7 and 28 days, the splitting tensile test at 28 days, the modulus of elasticity at 28 days. Two-way ANOVA results are presented in Table 5.9.

5.3.2.1. Compressive Strength

At 3 days, the mixes that are not significantly different are two groups:

- 0.5%hemp – 20%coarse and 0.75%hemp – 20%coarse.
- 1.0%hemp – 20%coarse and 1.0%hemp – 30%coarse.

All others are significantly different.

At 7 days, the mixes that are not significantly different are three groups:

- 0.5%hemp – 20%coarse, 0.75%hemp – 10%coarse, and 1.0%hemp – 10%coarse.
- 0.5%hemp – 10%coarse and 1.0%hemp – 30%coarse.
- 0.75%hemp – 20%coarse and 0.75%hemp – 30%coarse

All others are significantly different.

At 28 days, the mixes that are not significantly different are two groups:

- 0.5%hemp – 10%coarse, 0.75%hemp – 20%coarse, and 1.0%hemp – 30%coarse.
- 0.5%hemp – 30%coarse and 0.75%hemp – 30% coarse.

All others are significantly different.

Therefore, mainly the compressive strengths at different dates vary with most mixes; this variation can be attributed to the presence of fibers and to the difference in coarse aggregate amount, which could be related to the compressive strength more than the fibers.

5.3.2.2. Modulus of Rupture MOR

At 7 days, the mixes that are not significantly different are one group: 0.5%hemp – 10%coarse, 0.5%hemp – 20%coarse, 0.5%hemp – 30%coarse, 0.75% hemp – 20%coarse, and 1.0%hemp – 10% coarse.

At 28 days, mixes that are not significantly different are two groups:

- 0.5%hemp – 10%coarse and 1.0%hemp – 30%coarse.
- 0.5%hemp – 20%coarse, 0.5%hemp – 30%coarse, and 1.0%hemp – 20%coarse.

All others are significantly different.

The variation in the MOR, i.e. the flexural performance, could be attributed to the difference between mixes in terms of compressive strength and mostly the fibers orientation. Since the fibers are expected to bridge over a crack, the orientation of the fibers, parallel or perpendicular to the crack direction, could result in very distinct flexural performances.

Table 5.9. Two-Way ANOVA.

Compression (MPa) 3 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	9.8^{ab}	8.9^{cd}	8.3^{d}
0.75%	10.2^{a}	8.7^{cd}	7.6^{e}
1.0%	9.1^{bcd}	9.4^{abc}	9.6^{abc}
SEM	*0.20 (Standard Error of Mean)*		

Compression (MPa) 7 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	14.3^{a}	12.6^{abc}	11.4^{c}
0.75%	12.7^{abc}	12.2^{bc}	11.9^{bc}
1.0%	12.6^{abc}	13.4^{ab}	14.0^{a}
SEM	*0.39 (Standard Error of Mean)*		

Compression (MPa) 28 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	17.5^{cd}	16.7^{d}	17.8^{bcd}
0.75%	20.1^{a}	17.1^{cd}	17.9^{bcd}
1.0%	18.9^{ab}	18.1^{bc}	16.87^{cd}
SEM	*0.43 (Standard Error of Mean)*		

Modulus of Rupture MOR (MPa) 7 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	2.2^{c}	2.1^{c}	2.2^{c}
0.75%	2.6^{b}	2.3^{c}	2.4^{bc}
1.0%	2.3^{c}	2.4^{bc}	2.9^{a}
SEM	*0.09 (Standard Error of Mean)*		

Modulus of Rupture MOR (MPa) 28 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	2.9^{ab}	2.7^{abc}	2.7^{abc}
0.75%	3.1^{a}	2.6^{bdc}	2.5^{dc}
1.0%	2.2^{d}	2.8^{abc}	3.0^{ab}
SEM	*0.13 (Standard Error of Mean)*		

Splitting Tensile (MPa) 28 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	1.9^{d}	1.6^{f}	1.6^{f}
0.75%	1.8^{e}	2.2^{bc}	2.1^{c}
1.0%	2.2^{ab}	2.2^{bc}	2.3^{a}
SEM	*0.033 (Standard Error of Mean)*		

Modulus of Elasticity (MPa) 28 days Test

Hemp \ CR	**10%**	**20%**	**30%**
0.5%	$18{,}935^{b}$	$17{,}304^{c}$	$21{,}542^{a}$
0.75%	$14{,}919^{d}$	$20{,}678^{a}$	$16{,}134^{cd}$
1.0%	$18{,}966^{b}$	$16{,}959^{c}$	$17{,}088^{c}$
SEM	*497.7 (Standard Error of Mean)*		

CR: Coarse Aggregate.

Means with same Superscript are not significantly different.

5.3.2.3. Splitting Tensile

At 28 days, mixes that are not significantly different are two groups:

- 0.5%hemp – 20%coarse and 0.5%hemp – 30%coarse.
- 0.75%hemp – 20%coarse and 1.0%hemp – 20%coarse.

All others are significantly different.

Mostly, hemp mixes are similar in terms of splitting tensile results. The difference could be attributed to the amount of fibers present in addition to the course aggregate reduction.

5.3.2.4. Modulus of Elasticity

At 28 days, mixes that are not significantly different are three groups:

- 0.5%hemp – 10%coarse and 1.0%hemp – 10%coarse
- 0.5%hemp – 20%coarse, 1.0%hemp – 20%coarse, and 1.0%hemp – 30%coarse.
- 0.5%hemp – 30%coarse and 0.75%hemp – 20%coarse.

All others are significantly different.

The modulus of elasticity is attributed to the interaction between the concrete matrix and the fibers, and it is not dependent on one element without the other. Most hemp mixes are flexible and are similar in behavior in terms of elasticity

In summary, the effect of hemp fibers in addition to the coarse aggregate reduction in concrete mixes, can be variable and differences between mixes can be expected. The point is that the fibers orientation in the concrete can play a major role in the performance of the concrete mixes. However, the repeatability in the specimen number and the tests performed can show a certain trend in the performance of the new material.

5.4. Analytical Model for Phase One Results

According to Naaman et al. (1990), researchers have started investigating analytical modeling of fiber-reinforced concrete mixes using linear models; then after researchers investigated more sophisticated non-linear models (Barros et al. 1999, Mansur et al. 1999, and Junior et al. 2010).

In the current research, linear models were set and investigated. Based on the first phase tests results, linear models were developed in order to predict the compressive strength, modulus of elasticity, and flexural strength of samples tested. The models were developed based on test results of the samples tested for 0.5%, 0.75%, and 1.0% hemp volume fractions, and for 10%, 20%, and 30% coarse reductions; i.e., nine (3 x 3) mixes were incorporated in the analytical model development. As mentioned previously, three replicates were tested for each mix and test type.

The value used for hemp density was 1,400 kg/m^3. In the linear models, three variables were considered: the fibers volume fraction (V_f), the coarse aggregate reduction (CR), and the fibers aspect ratio (AR). The values of aspect ratio studied were 40, 50, and 60 (Section 3.3.1.2). Analysis revealed that the effect of AR was negligible and did not affect the predicted values for compressive strength, modulus of elasticity, and flexural strength. Thus, a fixed value of 50 was adopted in development of the linear models.

The models input are the control mix results in order to predict the hemp-reinforced mixes properties using different linear models in terms of compression, modulus of elasticity, and flexure at 28 days concrete age.

5.4.1. Compressive Strength Results

Many trials were investigated for the compressive strength linear model in order to optimize the predicted compressive strength. The control mix average result used was 23.4 MPa (Table 5.1). The sum of square of the error (E^2) between the predicted ($f_{predicted}$) and measured compressive strengths was calculated for all nine mixes. The linear model that minimized the sum of square of the error E^2 the most was selected.

Referring to Table 5.10, first the only variable included in the model was the volume fraction. The model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added as another variable along with the volume fraction in the model, but still the model was not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction separately was also investigated, the model was more sensitive to the coarse reduction than the V_f and AR but still not adequate enough in predicting values close to those measured. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included, as follows:

$$11.53 - 0.288 * f_{control} * (1 - CR/100) * (1 - V_f/100) + 0.0268 * AR * V_f$$

$f_{control}$ is the compressive strength result of the control mix.

Using this model, the sum of the square of the error was minimized to 6.21. The predicted data fitted well around the 45^o line when plotted against measured values (Figure 5.8), which justifies the adequacy of the model.

Table 5.10. Linear Model Trials for Prediction of Compressive Strength.

$f_{predicted}$	E^2	Variables
$144.37 - 5.45*f_{control}*(1-V_f/100)$	8.88	V_f only
$16.91 + 0.001*f_{control}*(AR*V_f)$	8.88	AR & V_f
$12.52 - 0.286*f_{control}*(1-CR/100)$	6.82	CR only
$12.58 - 0.285*f_{control}*(1-CR/100)*(1-V_f/100)$	6.88	CR & V_f
$11.53 - 0.288*f_{control}*(1-CR/100)*(1-V_f/100) + 0.0268*AR*V_f$	6.21	CR & V_f & AR

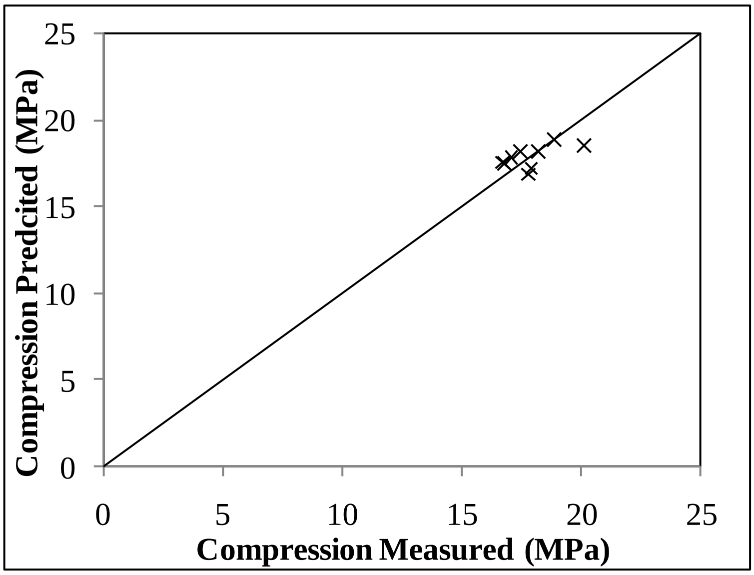


Figure 5.8. Best Fitted Data for the Compressive Strength Linear Model incorporating CR, V_f, and AR.

5.4.2. Modulus of Elasticity Results

Many trials were investigated for the modulus of elasticity linear model in order to optimize the predicted modulus. The modulus used for the control mix result was 23,754 MPa (Table 5.4). The sum of the square of the error (E^2) between the predicted ($E_{predicted}$) and measured moduli was calculated for all nine mixes and the minimum of the sum of the square of the error E^2 was targeted.

Referring to Table 5.11, first the volume fraction was only included, the model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added with the volume fraction in the model, the model was still not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction separately was also investigated and the model was still not adequate. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included, as follows:

$$23068.9 - 0.138*E_{control}*(1-CR/100)*(1-V_f/100) - 64.09*AR*V_f$$

$E_{control}$ is the modulus result of the control mix.

The sum of the square of the error was minimized to 32.44 and the data were best fitted. The predicted data fitted well around the 45^o line, but two outliers appeared to affect the model adequacy, as shown in Figure 5.9. Thus, the model was refined excluding data of two mixes: 0.5% Hemp-30% coarse and 0.75% Hemp-10% coarse. The model was improved as follows:

$$8641.3 + 0.495*E_{control}*(1-CR/100)*(1-V_f/100) + 0.837*AR*V_f$$

The predicted data fitted better around the 45^o line as illustrated in Figure 5.10 with the sum of the square of the error reduced to 9.39.

Table 5.11. Predicted Modulus of Elasticity Linear Model Trials (Square Error E^2 is Divided by 10^6).

$E_{predicted}$	$E^2/10^6$	Variables
$-929.369 + 0.805*E_{control}*(1-V_f/100)$	36.43	V_f only
$1074.742 + 0.0176*E_{control}*(AR*V_f)$	265.91	AR & V_f
$20650.2 - 0.136*E_{control}*(1-CR/100)$	36.24	CR only
$20536.1 - 0.131*E_{control}*(1-CR/100)*(1-V_f/100)$	36.29	CR & V_f
$23068.9 - 0.138*E_{control}*(1-CR/100)*(1-V_f/100) - 64.09*AR*V_f$	32.44	CR & V_f & AR
$8641.3 + 0.495*E_{control}*(1-CR/100)*(1-V_f/100) + 0.837*AR*V_f$	9.39	CR & V_f & AR

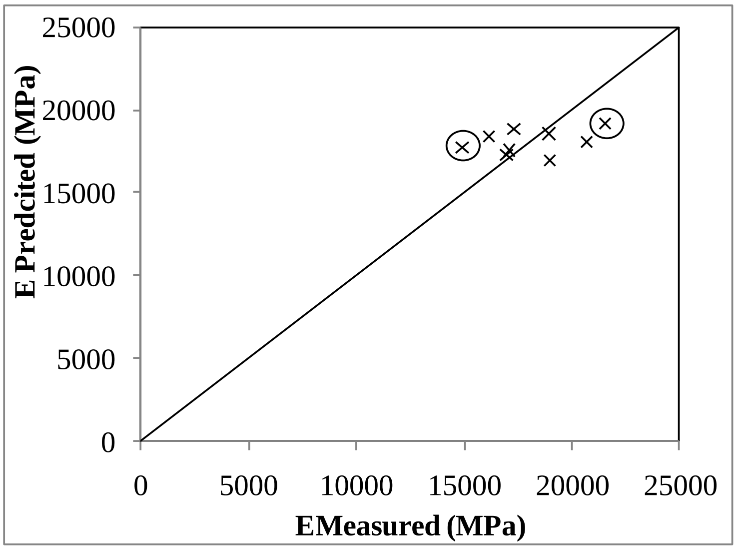


Figure 5.9. Fitted Data for the Modulus of Elasticity Linear Model with CR, V_f, and AR (Outliers Circled).

5.4.3. Flexure Results

Many trials were investigated for the beam flexure test maximum load linear model in order to optimize the predicted flexure peak load. The control mix average result used was 23.35 kN (MOR data Table 5.2).

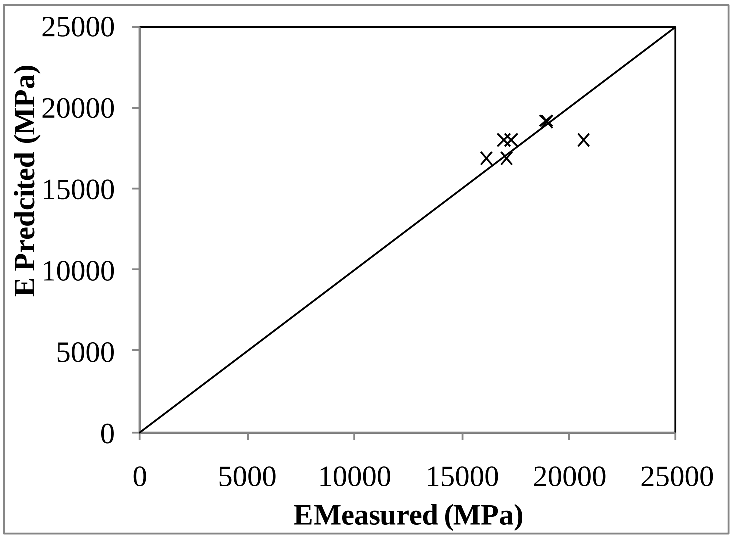


Figure 5.10. Fitted Data for the Refined (Outliers Excluded) Modulus of Elasticity Linear Model with CR, V_f, and AR.

Table 5.12. Predicted Flexure Maximum Load Linear Model Trials.

$P_{predicted}$	E^2	Variables
$-249.46 + 10.70*P_{control}*(1-V_f/100)$	36.29	V_f only
$21.59 - 0.0013*P_{control}*(AR*V_f)$	37.15	AR & V_f
$19.16 - 0.061*P_{control}*(1-CR/100)$	37.95	CR only
$19.07 - 0.066*P_{control}*(1-CR/100)*(1-V_f/100)$	36.30	CR & V_f
$20.32 - 0.063*P_{control}*(1-CR/100)*(1-V_f/100) - 0.0316*AR*V_f$	36.99	CR & V_f & AR
8.61 + 0.510*Pcontrol*(1-CR/100)*(1-Vf/100) + 0.0605*AR*Vf	11.49	CR & V_f & AR

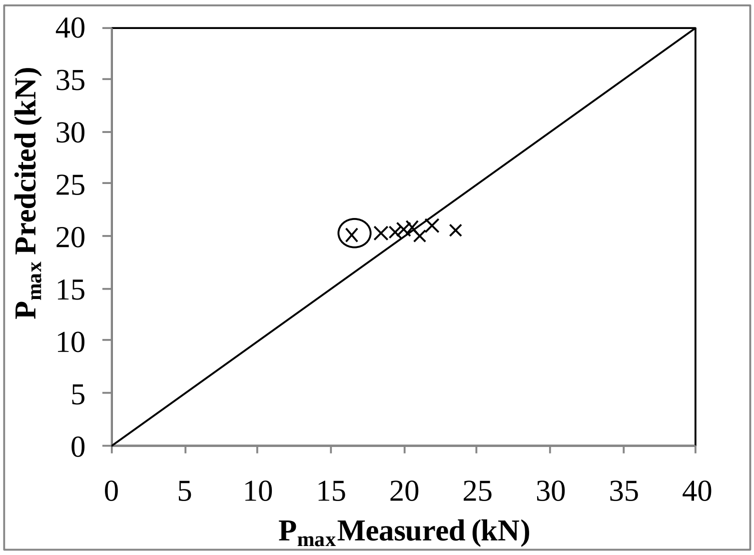


Figure 5.11. Fitted Data for the Flexure Maximum Load Linear Model with CR, V_f, and AR (Outlier Circled).

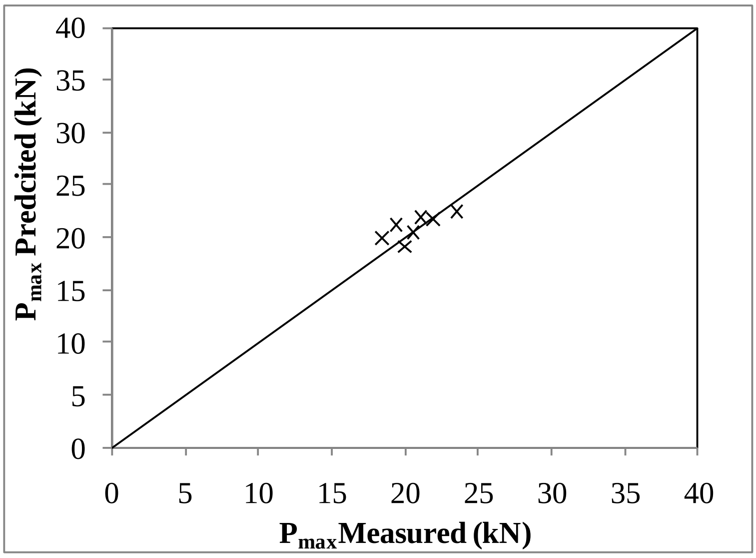


Figure 5.12. Fitted Data for the Refined (Outlier Excluded) Flexure Maximum Load Linear Model with CR, V_f, and AR.

The sum of the square of the error (E^2) between the predicted ($P_{predicted}$) and measured peak load was calculated for all nine mixes and the minimum of the sum of the square of the error E^2 was targeted. It is worth noting that the orientation and distribution of fibers in every specimen may be different and the maximum load variation cannot be expected even for the same fiber-concrete mix. Besides, the stress plane in the flexure beam specimens is not linear and not one dimensional. Note that in the literature the prediction of flexure maximum loads is rarely considered, mostly the compressive strength and modulus of elasticity instead.

Referring to Table 5.12, first the volume fraction was only included, the model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added with the volume fraction in the model, and the model was not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction separately was also investigated and the model was still not adequate. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included, as follows:

$$20.32 - 0.063*P_{control}*(1-CR/100)*(1-V_f/100) - 0.0316*AR*V_f$$

$P_{control}$ is the peak flexure load of the control mix.

The sum of the square of the error was minimized to 36.99 and the data were best fitted. The predicted data fitted around the 45^o line, but one outlier appeared to affect the model adequacy, as shown in Figure 5.11. Thus, the model was refined excluding the data of mix: 1% Hemp - 10% coarse. The model was improved as follows:

$$8.61 + 0.510*P_{control}*(1-CR/100)*(1-V_f/100) + 0.0605*AR*V_f$$

The predicted data fitted well around the 45^o line, Figure 5.12, with sum of the square of the error reduced to 11.49.

5.5. Summary and Conclusion

Phase one was aimed to further investigate the hemp mixes, in order to determine optimal hemp mixes which can be adopted in the following phase, where structural beam elements will be introduced and investigated.
Therefore a full scale testing set was launched in phase one. A control mix, a polypropylene mix, and ten hemp mixes were considered. The hemp volumetric fraction was varied between 0.5 and 1% by concrete volume. A coarse aggregate reduction of 10 to 30% by concrete volume was also included. Note that the 10%, 20%, and 30% coarse reduction by concrete volume is equivalent to 18.2%, 30.6%, and 46.3% coarse reduction from the control original coarse aggregate quantities, respectively.

The tests considered are compressive strength, flexure, splitting tensile, modulus of elasticity, thermal conductivity, density, and slump tests. A statistical analysis using ANOVA method was also included in order to be able to significantly determine whether differences exist among all mixes tests results.

The compressive strength results indicated that the cylinder tests, prepared with different fibers volumetric ratios and reductions in coarse aggregate, resulted in a decrease in the compressive strength with the increase in coarse aggregate reduction.

As for the flexure tests, the load-deflection curves results showed the ductile behavior of the fiber-reinforced concrete composite after the peak load is reached. The ductile behavior is directly related to the toughness of the composite material. The control specimen results showed the brittle failure of plain concrete after the peak load is reached. Although the modulus of rupture was less than that of control mix, the ductile behavior after the maximum load was noticeable in fiber-reinforced concrete specimens.

For the splitting tensile tests, the results indicated that the 0.75% and 1% hemp volume fractions were sufficient and adequate as an optimal substitute to the coarse reduction.

The modulus of elasticity of hemp mixes showed a decrease compared with that of the control mix. These results were consistent with the load-deflection curves, shifted to the right, implying a reduction in the stiffness.

The thermal conductivity test showed that the presence of sufficient hemp fibers would substantially improve the thermal properties of concrete mixes, resulting in an insulating concrete.

The density results of hemp mixes, as compared to that of the control mix, were less by an average of 5%.

The slump test results showed that for hemp mixes it would not be practical to go beyond 1% volumetric fraction, because of the hemp absorption capability.
Note that, comparing to the polypropylene mix results with no aggregate reduction, all hemp mixes results compared well or even better in most cases.

Statistical analysis was used to determine all significant differences between various mixes tests results, at a confidence level of 95%. It was shown that the compressive strength test results were significantly less compared to that of the control mix. In term of MOR, most hemp mixes were significantly less than that of the control mix. Most of the splitting tensile test results were not significantly different and did compare well with the control mix result. The modulus of elasticity test results were all significantly less than that of the control result. Moreover, comparing between the various hemp mixes, a two-way ANOVA showed that in most cases there is a significnat difference in the tests results. Since most hemp mixes are different in terms of the fibers volume fraction and the coarse aggregate reduction, such signifance would be expected.

Linear models were set and investigated for the first phase results of the compressive strength, modulus of elasticity, and flexure tests. The linear models were shown to acceptabely predict the hemp-fiber concrete mixes, based on the control results as input data for the models.

In order to proceed with the research, two hemp mixes were selected in addition to a control mix, to prepare and investigate structural beam elements. These three concrete mixes will be tested on reinforced concrete structural beam elements, and three modes of failure: flexure, shear, and bond will be investigated.

CHAPTER 6

PHASE 2 RESULTS AND ANALYSIS

6.1. Introduction

In the second phase of the research program, three mixes of Phase 1 were selected and integrated in structural beam elements to investigate the behavior of the mixes in the presence of steel reinforcement and under bending, shear, and bond splitting modes of failure. The three concrete mixes were: a control mix with no fibers (Control), a mix with hemp volume fraction of 0.75% and a coarse aggregate reduction of 20% by volume of concrete (0.75%Hemp-20%coarse), and a mix with hemp volume fraction of 1% and a coarse aggregate reduction of 20% by volume of concrete (1%Hemp-20%coarse). Properties of Phase 2 concrete mixes are presented in Table 6.1 in terms of the standard cylinders compressive strength and the slump tests.

Six beams were prepared with each type of the three mixes: two to fail in bending or flexural mode, two to fail in shear mode, and two were designed to fail in bond splitting mode of failure. Replicates were used to check and verify the validity of the test results. A total of eighteen beams were prepared and casted. The beams types representing the modes of failure were detailed in chapter 3 (Section 3.3.3)

6.2. Phase 2 Test Results

The load-deflection curves were plotted for all beams and compared with the control specimens. The curves are used to indicate the difference in toughness, ductility, and post-ultimate behavior. Also, the crack widths were measured at beams mid-span, under load P, and at splices end points for different beam types.

Table 6.1. Phase 2 Concrete Properties.

Mix Type	Compressive Strength (kg/cm^2)			Slump (cm)
	7 Days	28 Days	%Difference to Control (at 28 Days)	
Control	222	270	-	25
0.75%Hemp-20%coarse	152	189	-30%	17
1%Hemp-20%coarse	156	215	-20%	8

Typical beam specimens are illustrated in Figures 6.1, 6.3, and 6.5. Three beams of every type or mode of failure for the three mixes are shown, and the remaining tested beams are shown in Appendix 1.

Note that for all tested beams, there was a consistent agreement between the load-deflection curves, the stress in bottom bars, and the crack development results.

In general, when a crack is prevented from opening, another crack initiates. Therefore, in fiber-reinforced concrete and when the fibers amount is adequate, more small cracks are observed. For the hemp fibers considered here, more cracks were observed in the case with the 1% hemp mixes than with the case of 0.75% hemp mixes, when compared to control mixes. It is clear that with the hemp fibers presence, the fiber beams develop a large number of small-width cracks and allow for higher loads to be reached as the cracks develop upward prior to failure. Generally, by comparing the developed crack along mid-span in Figures 6.1, 6.3, and 6.5, it could be observed that in the presence of fibers a higher load was reached while the crack did not extend as much as in the control specimens.

6.2.1. Flexure Beams

For the beam specimens set to fail in the flexure mode, six beams were prepared for the three mixes, i.e. two beams for every mix type. Figure 6.2 shows the load-deflection curves of all six flexure beams: two control mix specimens F1 and F2, two 0.75%Hemp-20% coarse mix specimens F1 and F2, and two 1%Hemp-20% coarse mix specimens F1 and F2.

The flexure beams mode of failure can be described as follows. The first crack initiated in the tension zone when the stress reached the concrete tensile capacity; as the load was increased, the cracks developed along the entire beam width, and other cracks initiated in the shear zone (near supports). Finally, failure occurred when the shear and/or flexure capacity was reached. Failure was anticipated by multiple cracks that developed near the support on the left or right side. Schematic view of a cracked flexural beam is shown in Figure 6.1. When a crack is prevented from opening, another crack initiates. Thus, more small cracks are observed in the 1.0%Hemp-20%coarse than in the 0.75%Hemp-20%coarse, when compared to control mixes. In the hemp fibers presence, both flexure beams 1.0%Hemp-20%coarse and 0.75%Hemp-20%coarse developed a large number of small-width cracks and allow for higher loads to be reached as the cracks develop upward prior to failure.

Comparing the six beams, the presence of hemp fibers resulted in a post-ultimate ductile behavior. The two replicates or identical specimens for each mix type exhibited comparable behavior and ultimate load, thus adding to the reliability of tests results.

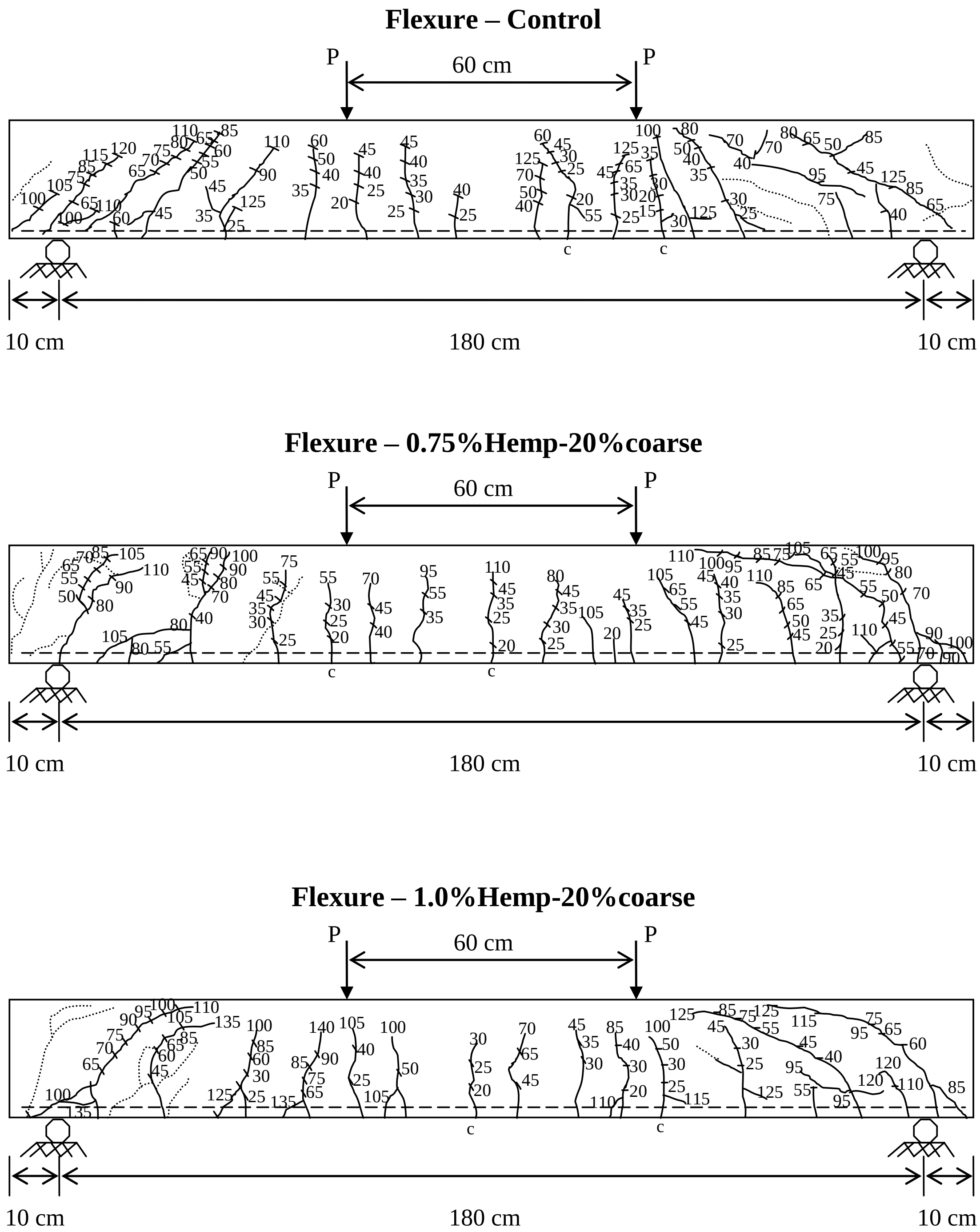


Figure 6.1. Schematic View of the Cracked Flexural Beam Specimens (Control, 0.75%Hemp-20%coarse, and 1.0%Hemp-20%coarse). (c Is the Location of Crack Measure, Nearest to Mid-span and to Under One of Loads).

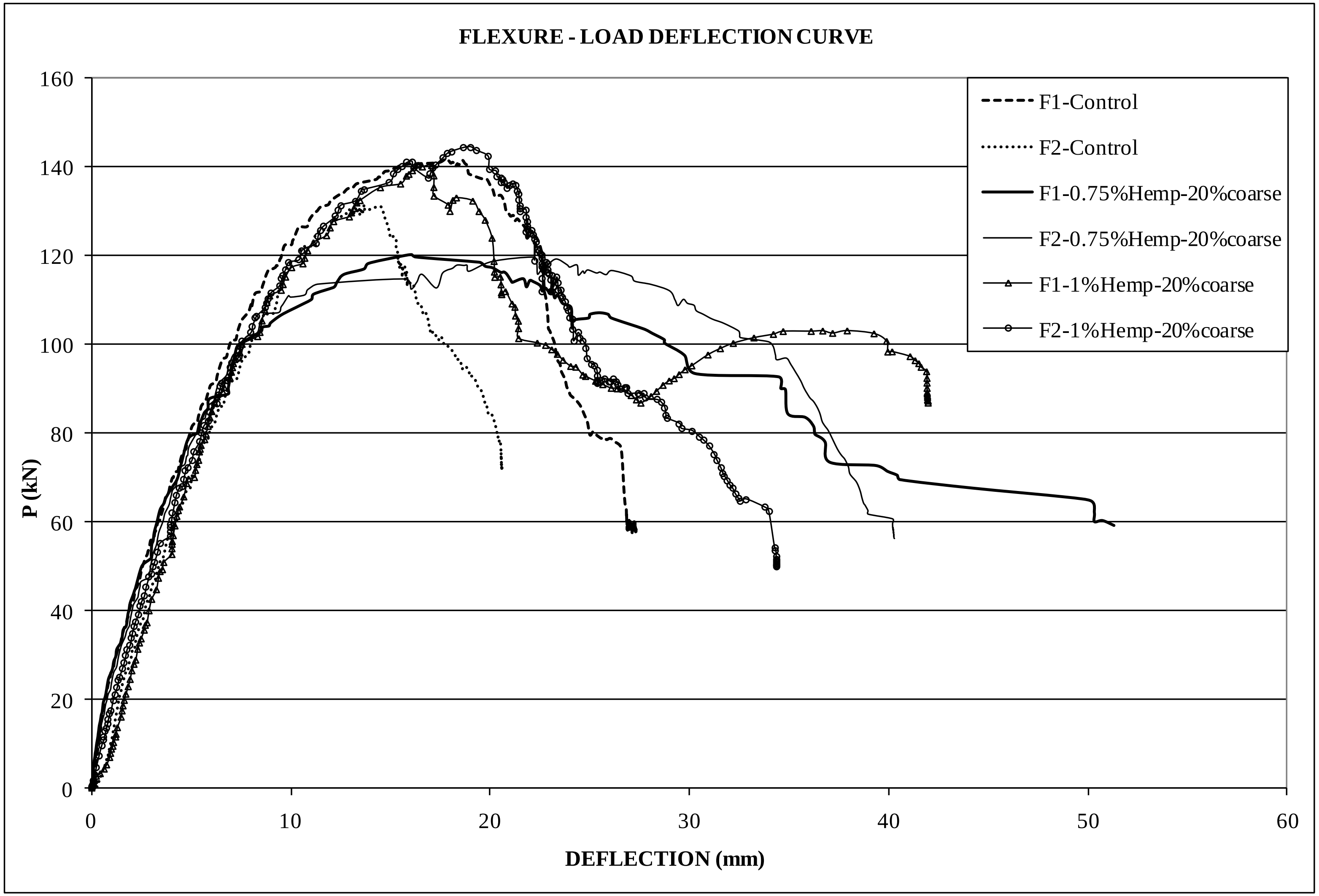


Figure 6.2. Load-Deflection Curves for Flexure Beams with Two Specimens for Every Mix.

Although the concrete compressive strength of the hemp mixes was less by 20-30% as compared to the control mix, the maximum flexural loads of the hemp beam specimens were comparable to that of the control beam. The average maximum flexural load was 135 kN for the control beams, 120 kN for the 0.75% hemp beams, and 142 kN for the 1% hemp beams. Thus, the 1% hemp mixes resulted in maximum flexural load compared to the control beam but better ductile behavior, and at the same time a saving of 20% of the coarse aggregates content.

6.2.2. Shear Beams

For the beam specimens set to fail in the shear mode, six beams were prepared for the three mixes, i.e. two replicate beams for every mix type. The load-deflection curves, for the six shear beams, are shown in Figure 6.4: two control mix specimens S1 and S2, two 0.75%Hemp-20% coarse mix specimens S1 and S2, and two 1%Hemp-20% coarse mix specimens S1 and S2. Whereas the control beams experienced sharp drop in load after reaching maximum load, the four beams with hemp fibers exhibited post-ultimate ductile behavior.

Similar to the flexure beam specimens, the first crack initiated in the tension zone; however, failure occurred in the shear zone, because the beams are under-designed for shear. These observations agree with the strain development in the bottom bars. For the shear beams failure was anticipated by the cracks that developed near the support on the left or right side, in the shear zone. A schematic view of the cracked shear beam is shown in Figure 6.3. When a crack is prevented from opening, another crack initiates. Thus, more small cracks are observed in the 1.0%Hemp-20%coarse than in the 0.75%Hemp-20%coarse, when compared to control mixes.

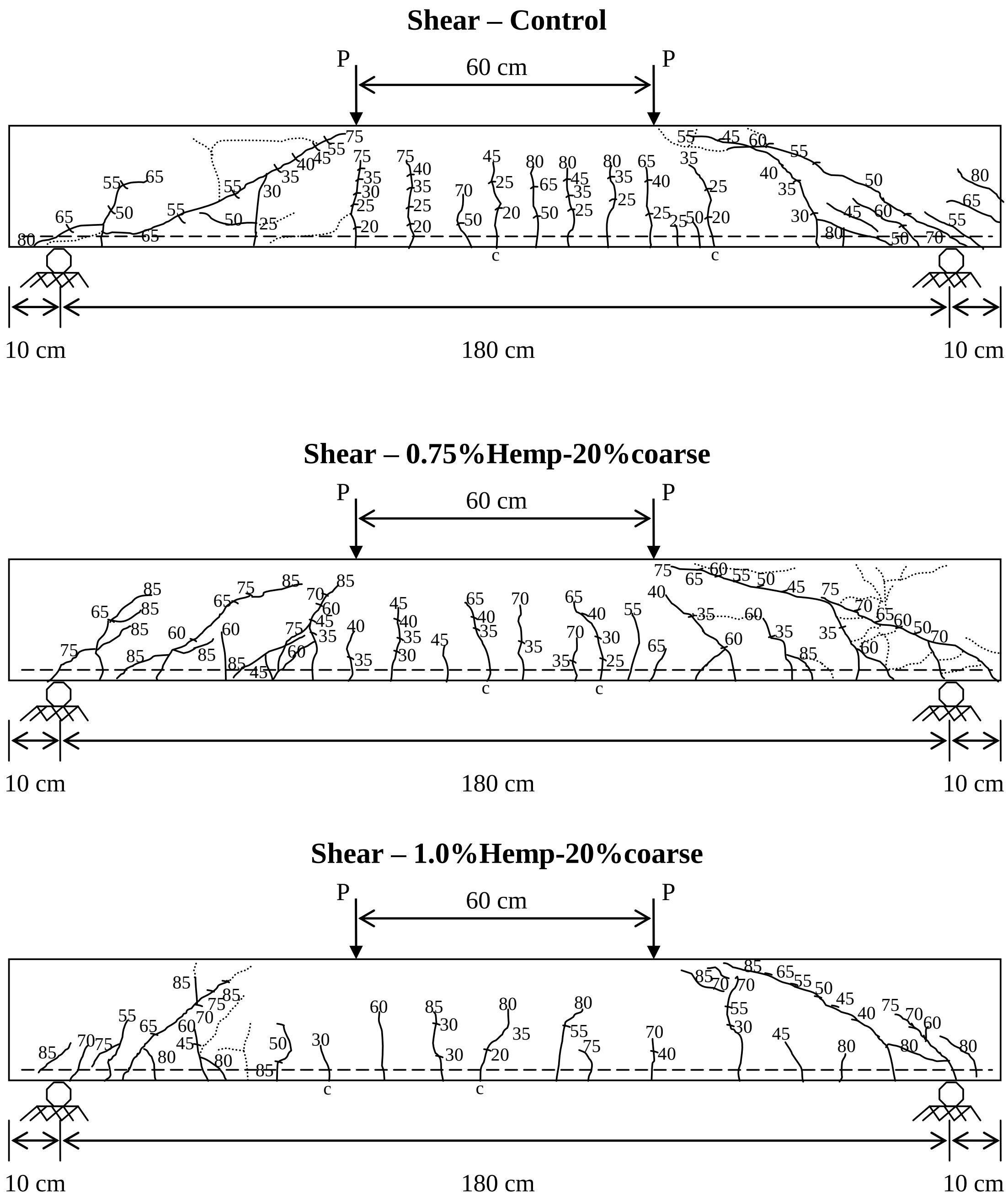


Figure 6.3. Schematic View of the Cracked Shear Beam Specimens (Control, 0.75%Hemp-20%coarse, and 1.0%Hemp-20%coarse). (c Is the Location of Crack Measure, Nearest to Mid-span and to Under One of Loads).

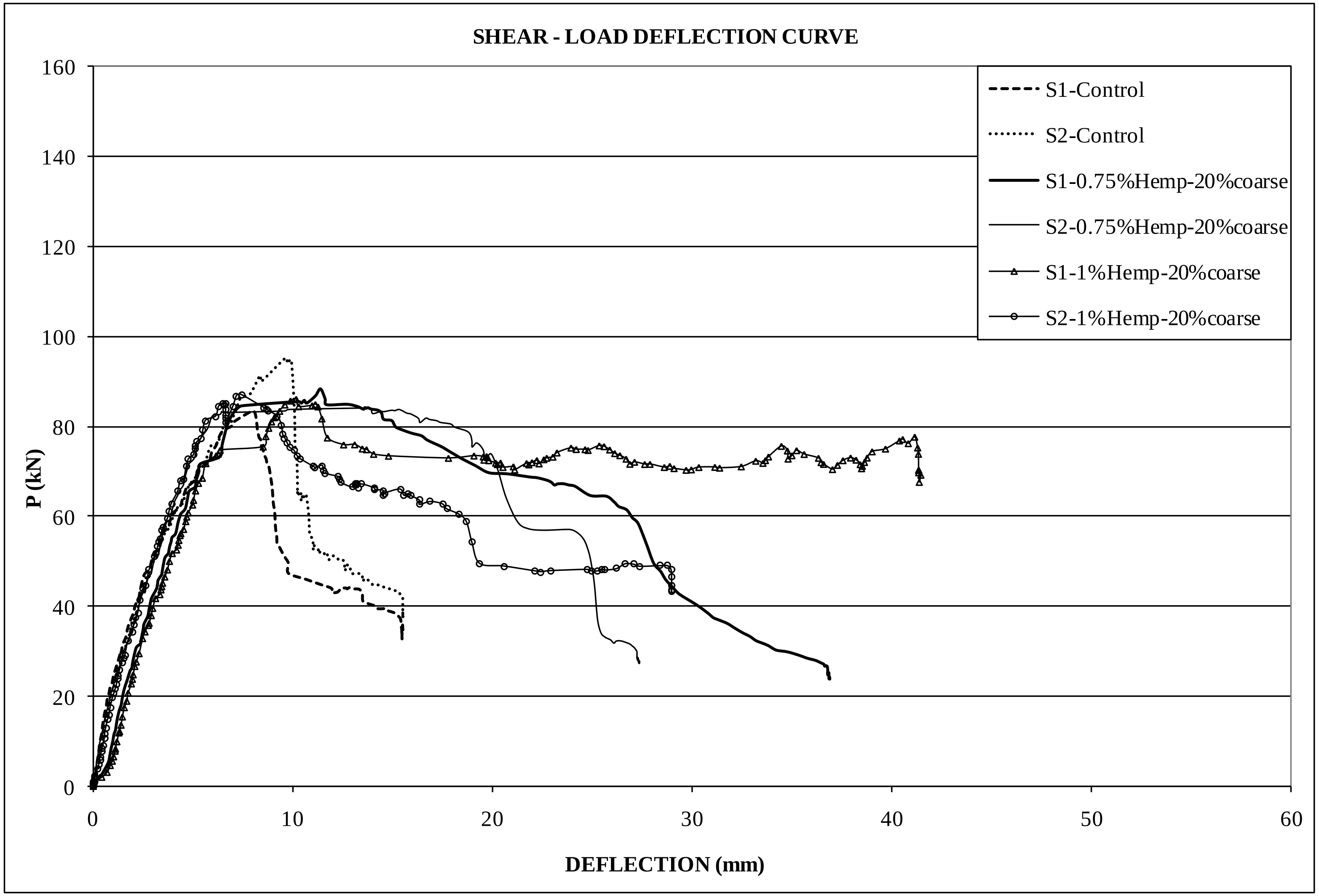


Figure 6.4. Load-Deflection Curves for Shear Beams with Two Specimens for Every Mix.

In the hemp fibers presence, both shear beams 1.0%Hemp-20%coarse and 0.75%Hemp-20%coarse developed a large number of small-width cracks and allow for higher loads to be reached as the cracks develop upward prior to failure.

The peak loads of all beams were comparable. The average maximum shear load was 90 kN for the control beams, 85 kN for the 0.75% hemp beams, and 87 kN for the 1% hemp beams. Thus, effectively there was no reduction in the maximum loads of the shear beams due to the incorporation of fibers, while the coarse aggregate content was reduced by 20% by volume, and a ductile post-ultimate behavior was gained.

6.2.3. Bond Beams

For the beam specimens set to fail in the bond splitting mode, six beams were prepared for the three mixes, i.e. two replicate beams for every mix type. The load-deflection curves for the six bond beams are shown in Figure 6.6: two control mix specimens B1 and B2, two 0.75%Hemp-20% coarse mix specimens B1 and B2, and two 1%Hemp-20% coarse mix specimens B1 and B2. Similar to the shear beams, the two control beams had a sharp drop in load after ultimate indicating brittle behavior. Whereas the four beams with hemp fibers exhibited more ductile post ultimate load-deflection behavior.

The first crack initiated in tension zone, but failure occurred along the mid-span where the provided splices length 30.5 cm (12 inch) were less than the required design length. Failure splitting cracks were observed at the bottom side in the splice region. Note that, as in Table 6.6, the longitudinal bars elongation is far below the flexure result, since the beams were under-designed for the splice load. Schematic view of the cracked bond beam is shown in Figure 6.5.

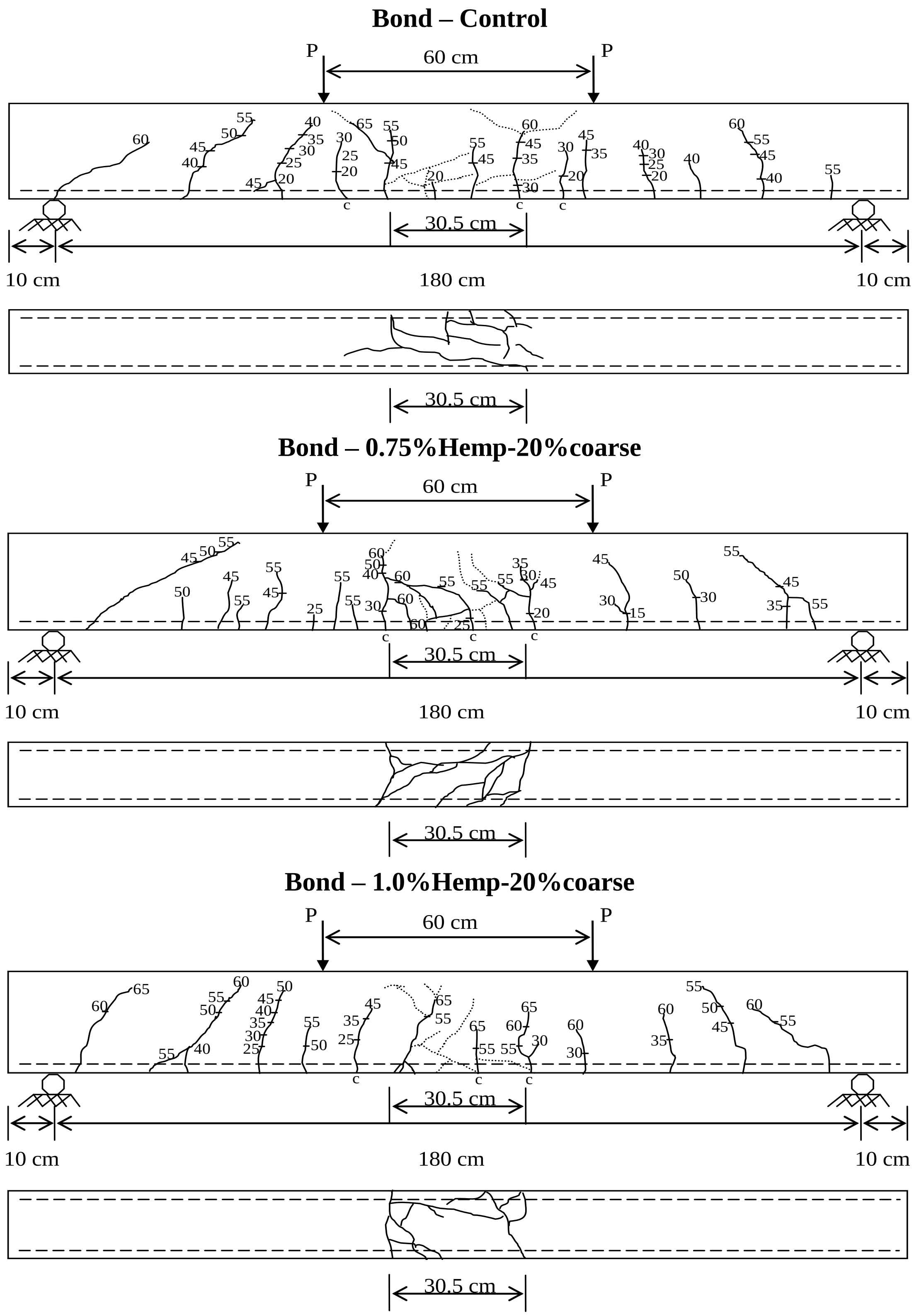


Figure 6.5. Schematic View (Side and Bottom) of the Cracked Bond Beam Specimens (Control, 0.75%Hemp-20%coarse, and 1.0%Hemp-20%coarse). (c Is the Location of Crack Measure, Nearest to Mid-span and Splice Ends).

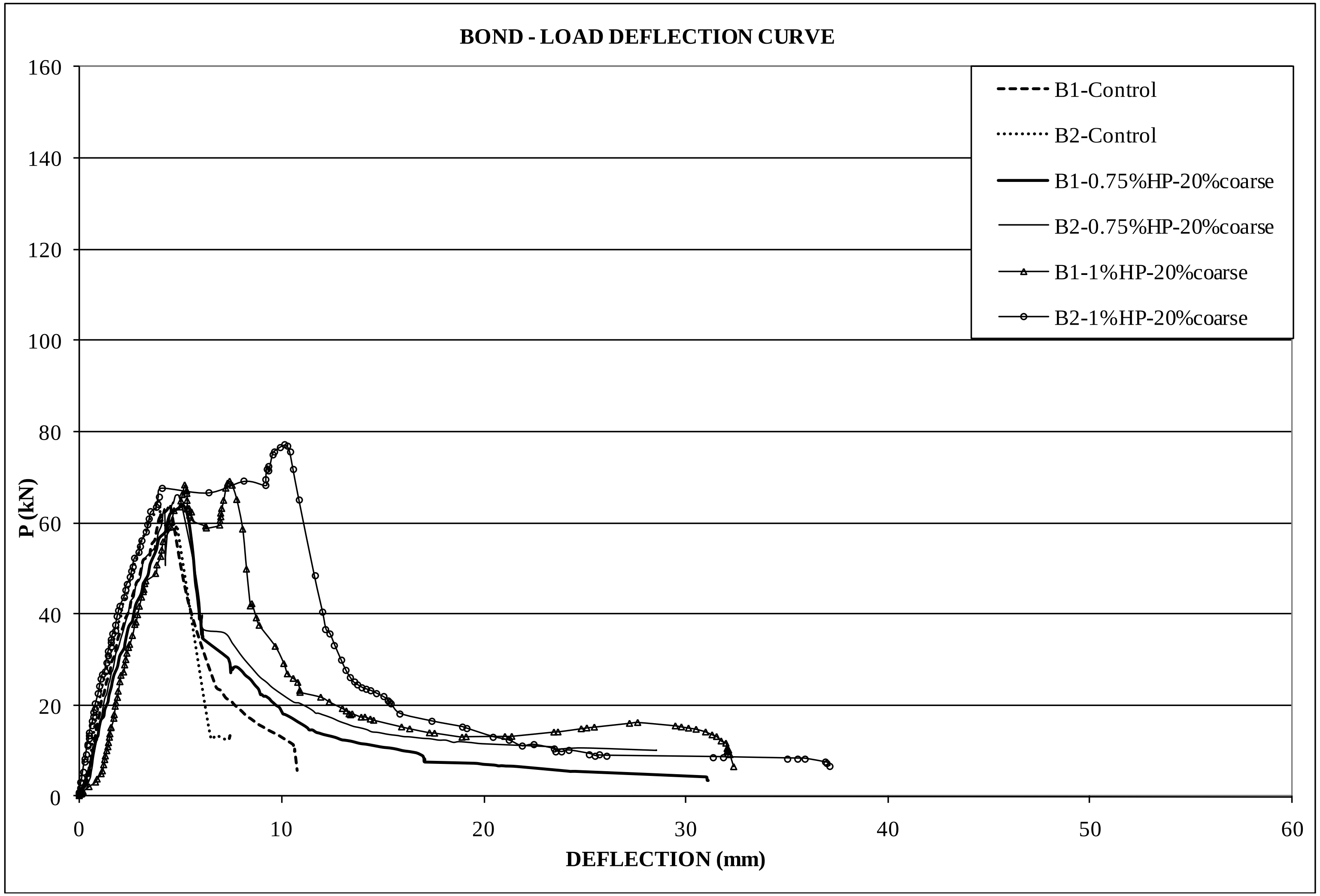


Figure 6.6. Load-Deflection Curves for Bond Beams with Two Specimens for Every Mix.

When a crack is prevented from opening, another crack initiates. Thus, more small cracks are observed in the 1.0%Hemp-20%coarse than in the 0.75%Hemp-20%coarse, when compared to control mixes. In the hemp fibers presence, both bond beams 1.0%Hemp-20%coarse and 0.75%Hemp-20%coarse developed a large number of small-width cracks and allow for higher loads to be reached as the cracks develop upward prior to failure.

Comparing the six beams, the peak loads for hemp beams were comparable. The average maximum bond load was 65 kN for the control beams, 65 kN for the 0.75% hemp beams, and 73 kN for the 1% hemp beams. Thus, the presence of the hemp fibers did not adversely affect the maximum load of beams failing in bond splitting mode, but resulted in a post-ultimate ductile behavior, and a 20% reduction of coarse aggregate.

6.2.4. Toughness and Ductility

To evaluate the effect of hemp fibers on toughness and ductility of the beam specimens regardless of failure mode (flexure, shear, or bond) the area under the load-deflection curve was used as an indicator (refer to Table 6.2). Comparing the different beam types, the flexure beams have the largest area since the peak load reached is higher than the shear and bond beams due to the presence of adequate shear and flexure reinforcement.

In general, for the three modes of failure tested, beams with hemp fibers showed more ductility or toughness than the control beams as indicated by the increase of the area under the load-deflection curves.

For the flexure beams, the area under the load-deflection curve was calculated for a deflection range between zero and 35 mm deflection range. Note that whenever the maximum deflection was less than 35 mm, the maximum deflection was considered instead of 35 mm. The effect of the presence of the hemp fibers in the concrete mixes is clearly evident. The areas for the control, 0.75% Hemp, and 1% Hemp mixes are on average 2321, 3787, and 3610 kN-mm, respectively, i.e. almost a 50% increase in the load-deflection area is provided by the presence of hemp fibers. The hemp specimens allowed for a larger deflection as compared with the control specimens. The final average deflections reached for the control, 0.75% hemp, and 1% hemp specimens were 24, 45, and 30 mm, respectively. Under dynamic loading, the toughness or ductility in the flexure beams is more crucial than the peak load. Thus, the presence of hemp fibers would result in more energy absorption prior to final failure, as compared with non-ductile and rapid failure for the control specimens.

For the shear beams, the area under the load-deflection curve was calculated between zero and 25 mm deflection range. Note that whenever the maximum deflection was less than 25 mm, the maximum deflection was considered instead of 25 mm. Since the beams were under-designed in shear, the peak load of the shear beam was expected to be less than that reached with the flexure beams. However, and as noted before, the peak load of the shear beams was not significantly affected by the presence of fibers, although the coarse aggregates were less by 20% of concrete volume. Moreover, the post-ultimate behavior of the hemp fiber beams was more ductile. The area under the load-deflection curves for the control, 0.75% hemp, and 1% hemp mixes were on the average 819, 1692, and 1495 kN-mm, respectively, indicating almost double the area with the hemp mixes. The maximum deflection reached for the control, 0.75% hemp, and 1% hemp mixes were on the average 15, 30, and 35 mm, respectively. The increase in maximum deflection accompanied with a gradual decrease in the load after reaching maximum prior to failure is more favorable than a rapid failure and a rapid drop of load as is the case with the control specimens. The hemp fibers provided a ductile behavior in addition to a 20% savings on coarse aggregates.

Table 6.2. Area under Load Deflection Curves (Deflection between 0 and Maximum Value).

		Area (kN-mm)	Max. Deflection (mm)
Flexure Beams	F1-Control	2821	35
	F2-Control	1821	35
	F1-0.75%Hemp-20%coarse	3917	35
	F2-0.75%Hemp-20%coarse	3656	35
	F1-1%H Hemp-20%coarse	3394	35
	F2-1%H Hemp-20%coarse	3825	35
Shear Beams	S1-Control	859	25
	S2-Control	778	25
	S1-0.75%Hemp-20%coarse	1683	25
	S2-0.75%Hemp-20%coarse	1700	25
	S1-1%Hemp-20%coarse	1771	25
	S2-1%Hemp-20%coarse	1218	25
Bond Beams	B1-Control	274	15
	B2-Control	265	15
	B1-0.75%Hemp-20%coarse	582	15
	B2-0.75%Hemp-20%coarse	465	15
	B1-1%H Hemp-20%coarse	607	15
	B2-1%H Hemp-20%coarse	1898	15

For the bond beams, the area under the load-deflection curve was calculated between zero and 15 mm deflection range. Note that whenever the maximum deflection was less than 15 mm, the maximum deflection was considered instead of 15 mm. Since the beams were designed to fail in bond splitting mode of failure, the peak load reached was expected to be less than that reached with the flexure beams and further less than that with the shear beams. However, the peak load in the hemp mixes beams was comparable with that of the control beams. The areas under the load-deflection curves for the control, 0.75% hemp, and 1% hemp mixes were on the average 270, 524, and

1253 kN-mm, respectively. The values again indicate the positive effect of hemp fibers on ductility.

For all beam types and modes of failure, the hemp fibers presence modified the concrete material toward a more ductile and energy absorbent material, while saving on 20% of the coarse aggregates by volume of concrete. Even though the hemp fiber beams had 20% volume reduction of coarse aggregates, the peak loads after hemp beams were compared to the control beams for all modes of failure tested. Add to that the hemp fiber beams exhibited a ductile behavior which is very favorable under dynamic load applications such as pavements, earthquake structures, and others.

6.2.5. Crack Width Measures

The crack width was measured manually using a crack width comparator at different locations for every beam type.

For the flexure beams specimens, flexural cracks in the constant moment region were measured and monitored to study the effect of hemp fibers on the width of the flexural cracks. These consisted of the average of two measures one at mid-span and one under one of the applied loads P (left or right), was determined at about 2 cm above the beam bottom side. Note that in case no cracks appeared exactly at mid-span or under applied load, the location of the measured cracks was at the nearest location to mid-span and under the applied load.

Table 6.3 presents the average crack width measure for different mixes and Figure 6.1 shows the crack measure location; the cracks locations were selected for two reasons:

1. Cracks at mid-span were larger in width than those under load P, which resulted in better accuracy in measuring crack width with the crack width comparator.
2. Usually in a simply supported structural beam element and under the third-point load set-up, flexural cracking at mid-span is more critical than that under the applied load P.

As an example, at a load P of 80 kN, the crack width ranged from 0.30 to 0.33 mm, 0.18 to 0.40 mm, and 0.20 to 0.28 mm for the control, 0.75% hemp, and 1.0% hemp mixes, respectively. Also, at 110 kN (close to peak load), the crack width ranged from 0.37 to 0.45 mm, 0.28 to 0.48 mm, and 0.28 to 0.35 mm, for the control, 0.75% hemp, and 1.0% hemp mixes, respectively. It is evident that the average crack width was the least with the 1.0%Hemp-20%coarse mix.

For the shear beams specimens, flexural cracks in the constant moment region were measured and monitored to study the effect of the fibers on the width of the flexural cracks. The average of two measures one at mid-span and one under one of the applied loads P (left or right) was determined. Note that in case no cracks appeared exactly at mid-span or under applied load, the location of the measured cracks was at the nearest location to mid-span and under the applied load.

Table 6.4 presents the average crack width measure for different mixes and Figure 6.3 shows the crack measure location; the cracks locations were selected for the same reasons as in the flexure beam case.

As an example, at a load P of 45 kN, the crack width ranged from 0.10 to 0.18 mm, 0.13 to 0.18 mm, and 0.08 to 0.09 mm for the control, 0.75% hemp, and 1.0% hemp mixes, respectively. Also, at 80 kN (close to peak load), the crack width ranged from 0.13 to

0.25 mm, 0.23 to 0.29 mm, and 0.18 to 0.25 mm for the control, 0.75% hemp, and 1.0% hemp mixes, respectively.

Table 6.3. Average Crack Width of Flexure Beams at Two Locations: Mid-Span and Under One of the Loads P.

	F1-CL	F2-CL	F1-0.75HP-20c	F2-0.75HP-20c	F1-1.0HP-20c	F2-1.0HP-20c
Load P(kN)	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**
15	-	0.04	-	-	-	-
20	-	0.09	-	0.08	0.04	-
25	0.09	0.10	0.04	0.08	0.08	-
30	0.13	0.15	0.08	0.09	0.08	0.08
35	0.15	0.20	0.08	0.13	0.08	0.08
40	0.18	0.20	0.08	0.18	0.09	0.08
45	0.20	0.25	0.10	0.23	0.10	0.09
50	0.20	0.25	0.13	0.25	0.10	0.10
55	0.20	0.25	0.13	0.25	0.13	0.13
60	0.20	0.28	0.15	0.28	0.13	0.15
65	0.25	0.30	0.18	0.32	0.18	0.20
70	0.25	0.30	0.18	0.37	0.18	0.23
75	0.28	0.33	0.18	0.37	0.20	0.25
80	0.30	0.33	0.18	0.40	0.20	0.28
85	0.30	0.37	0.23	0.40	0.20	0.28
90	0.33	0.37	0.23	0.43	0.20	0.28
95	0.33	0.37	0.23	0.43	0.25	0.29
100	0.33	0.40	0.28	0.43	0.25	0.32
105	0.37	0.45	0.28	0.48	0.25	0.32
110	0.37	0.45	0.28	0.48	0.28	0.35
115	0.40	0.45	0.29	-	0.28	0.35
120	0.40	0.53	0.35	-	0.32	0.35
125	0.40	0.53	-	-	0.33	0.35
130	0.43	-	-	-	0.37	0.35
135	0.45	-	-	-	0.40	0.40
140	0.45	-	-	-	-	0.42

For the bond beams specimens, flexural cracks in the constant moment region outside the splice region were measured and monitored to study the effect of hemp fibers on the width of the flexural cracks. The average of three measures one at mid-span and two at both splice ends (left and right), was determined. Note that in case no cracks appeared exactly at mid-span or at splice ends, the location of the measured cracks was at the nearest location to mid-span and to splice ends.

Table 6.4. Average Crack Width of Shear Beams at Two Locations: Mid-Span and Under One of the Loads P.

	S1-CL	S2-CL	S1-0.75HP-20c	S2-0.75HP-20c	S1-1.0HP-20c	S2-1.0HP-20c
Load P(kN)	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**
10	0.04	-	-	-	-	-
15	0.08	0.04	-	-	-	-
20	0.10	0.08	-	-	0.04	-
25	0.10	0.08	0.08	0.04	0.04	0.04
30	0.13	0.10	0.08	0.04	0.08	0.04
35	0.15	0.10	0.08	0.10	0.08	0.08
40	0.15	0.10	0.10	0.15	0.08	0.09
45	0.18	0.10	0.13	0.18	0.08	0.09
50	0.18	0.10	0.13	0.18	0.10	0.09
55	0.18	0.10	0.18	0.18	0.10	0.10
60	0.23	0.13	0.18	0.18	0.13	0.18
65	0.23	0.13	0.20	0.20	0.15	0.20
70	0.23	0.13	0.20	0.25	0.15	0.20
75	0.23	0.13	0.20	0.29	0.18	0.25
80	0.25	0.13	0.23	0.29	0.18	0.25
85	-	0.13	0.23	-	0.20	0.25
90	-	0.15	-	-	-	-

Table 6.5 presents the average crack measure for different mixes and Figure 6.5 shows the crack measure location; the cracks locations were selected for two reasons:

1. racks outside the splice region were larger in width than those inside the splice region, which resulted in better accuracy in measuring crack width with the crack width comparator.
2. Usually in a structure, flexural cracking outside the splice region is more critical than that inside the splice region due to the fact that the steel area in the splice region is greater and the stresses are smaller along the splice than outside.

As an example, at a load P of 45 kN, the crack width ranged from 0.13 to 0.15 mm, 0.13 to 0.18 mm, and 0.06 to 0.10 mm for the control, 0.75% hemp, and 1.0% hemp mixes, respectively. Also, at 60 kN (close to peak load), the crack width ranged from 0.15 to

0.22 mm, 0.18 to 0.25 mm, and 0.12 to 0.13 mm for the control, 0.75% hemp, and 1.0% hemp mixes, respectively.

Table 6.5. Average Crack Width of Bond Beams at Three Locations: Mid-Span and at the Ends of Splices Left and Right.

	B1-CL	B2-CL	B1-0.75HP-20c	B2-0.75HP-20c	B1-1.0HP-20c	B2-1.0HP-20c
Load P(kN)	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**
20	0.08	-	0.05	0.03	0.03	-
25	0.08	-	0.07	0.05	0.03	0.03
30	0.09	0.08	0.08	0.08	0.08	0.05
35	0.10	0.09	0.13	0.09	0.08	0.05
40	0.13	0.13	0.15	0.09	0.09	0.06
45	0.13	0.15	0.18	0.13	0.10	0.06
50	0.13	0.17	0.20	0.14	0.10	0.07
55	0.13	0.17	0.21	0.16	0.10	0.09
60	0.15	0.22	0.25	0.18	0.12	0.13
65	-	-	-	0.30	0.13	0.13
70	-	-	-	-	0.13	-

For all beam types: flexure, shear, and bond, the presence of the hemp fibers reduced the average flexure crack width. For the 0.75% hemp mixes, the crack width was less or equal to the control beams cracks, while for the 1.0% hemp mixes the crack width was clearly less than the control beams values. Although the cracks in the hemp fibers beams are generally narrower than those in the control specimens, they were larger in number. The ability of the fiber beams to develop a large number of small-width cracks and allow for higher loads to be reached as the cracks develop prior to the failure is the main reason behind their ductile behavior. Fibers prevented excessive opening of developed cracks at failure, and therefore maintained the integrity of the beams. This observation in the crack width is expected, since the fibers role is to bridge over the crack width, resulting in a more ductile mode of failure. The crack width results are consistent with the load-deflection curves, since for all 18 tested beams the load deflection curves showed some toughness in terms of the area under curve, compared to the control beams, where a brittle mode of failure was observed.

6.2.6. Reinforcement Bars Elongation and Yield Limit

Based on the readings of the strain gages that were installed on each of the two T20 mm main reinforcement bars, the micro-strains were recorded. The strain was calculated by multiplying the strain gage reading by 10^{-6}, and then the steel stress limit was calculated by multiplying the strain by the steel modulus of elasticity (2×10^6 kg/cm^2). The average stress value of the main reinforcement is reported. The values for all tested beams are listed in Table 6.6. Based on the laboratory testing, the T20 mm yield limit was determined to be 6,360 kg/cm^2.

Considering the flexure beams, the developed stresses are close to the yield limit but did not reach it. The reinforcement bars in all tested shear and bond beams did not reach yield point. For comparison purposes, the cracked section analysis was performed on all beams and the steel stress (f_s) was determined accordingly. The results of the compressive strength identified and used from Table 6.1. The modulus of elasticity was determined based on the compressive strength as 15,115*sqrt(f'_c) in kg/cm^2. Also the service moment was determined based on the peak load as P*L/3. An example of the steel stress calculation using cracked section analysis is shown in Appendix 3.

For the flexure beams, the cracked section analysis shows that the steel bars in the control and 1.0% hemp fiber beams are very close to the yield; whereas, bars in the 0.75% fiber beams did not yield. The presence of fibers could be a factor that affected the yield limit for the flexure beams, since it is known from the Phase 1 results and the corresponding load-deflection curves that the hemp-reinforced concrete material is more flexible with less stiffness (based on calculated modulus of elasticity and area under curves). The ductility is therefore attributed mainly to the concrete mix more than to the main reinforcement.

Table 6.6. Stress Limits Developed in T20 mm Main Reinforcement Bars, with the Maximum Load and Correspondent Deflection.

Specimen No.	Measured Avg. Stress* (Kg/cm^2)	Maximum Load P (kN)	Calculated fs ** (Kg/cm^2)	Deflection at Maxi. Load (mm)
F1-CL	***	142.0	6178	17.8
F2-CL	***	131.4	5718	13.4
B1-CL	3268	64.0	2785	4.5
B2-CL	3449	65.2	2835	3.9
S1-CL	3744	83.5	3631	7.9
S2-CL	4409	95.2	4143	9.6
F1-0.75%HP-20%coarse	5474	120.2	5282	16.1
F2-0.75%HP-20%coarse	5709	119.9	5267	22.2
B1-0.75%HP-20%coarse	3498	63.8	2805	5.1
B2-0.75%HP-20%coarse	3206	66.1	2904	4.8
S1-0.75%HP-20%coarse	3771	88.3	3879	11.4
S2-0.75%HP-20%coarse	3672	84.1	3694	13.7
F1-1.0%HP-20%coarse	5470	140.4	6149	16.4
F2-1.0%HP-20%coarse	***	144.5	6328	19.0
B1-1.0%HP-20%coarse	2717	69.1	3023	7.4
B2-1.0%HP-20%coarse	3705	77.0	3371	10.1
S1-1.0%HP-20%coarse	4115	86.2	3773	10.2
S2-1.0%HP-20%coarse	2977	87.0	3810	7.4

** Yield limit for T20 mm Bars is 6360 kg/cm^2.*
*** Calculated steel stress from cracked section analysis, under maximum service load (P*L/3).*
****Unreliable since the measured stress value, after peak load was reached, was much larger than yield limit.*

6.3. Summary and Conclusions

Phase 2 was planned to investigate the effect of the hemp fibers in concrete mixes when integrated in structural beam elements. Three modes of failure were tested: (flexure, shear, and bond) coupled with three concrete mixes (control, 0.75%hemp-

20%coarse, and 1%hemp-20%coarse mixes) with two replicate beams considered for reliability and accuracy of results. In total, 18 beams were tested. The selection of the hemp mixes was based on Phase 1 results taking into account the performance and the mixing workability.

In all beam types, it was commonly observed that the hemp fibers addition resulted in a ductile behavior after the peak load was reached. Besides, for the hemp fibers beams, the peak loads were almost not affected while a 20% reduction in the coarse aggregates was possible.

The ductile behavior of the hemp fibers beams was demonstrated by the larger area under the load-deflection curves in addition to the larger deflection reached after the beam failure. Moreover, based on the crack width measures at different locations on every beam type, the effect of hemp fibers was illustrated in smaller cracks width but larger number of cracks, indicating a ductile behavior.

For all three mixes tested, the reinforcement bars in the flexure beams main reinforcement were close to the yield limit; whereas, those of the shear and bond beams did not yield. The ductility after the peak load was reached could be mainly attributed to the hemp-reinforced concrete rather than to the main reinforcement.

CHAPTER 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1. Research Summary

In the current research, the physical characteristics and structural performance of concrete using natural fibers were investigated. Aiming to develop a sustainable or “green” concrete, different agricultural fibers, considered as waste products, were incorporated in concrete mixes, in lieu of synthetic or industrial fibers. Besides, the possibility of reducing the coarse aggregate quantity in order to save on natural resource depletion was also considered.

While the use of industrial hemp fibers was the primarily subject of the research, other natural fibers such as banana and palm were included in the program, as well as selected synthetic fibers for comparison purposes. The core of the research focused therefore on the hemp fibers and the feasibility to incorporate in reinforced concrete buildings or other structural systems.

In proving the viability of natural fibers, the demand for hemp fibers in concrete production would be a major incentive to Lebanese farmers to grow this plant and benefit from the social impact on the habitat level of living.

The research was mainly divided into three phases: trial, first, and second phases.

The preliminary or trial phase investigated the possibility and the performance of different agricultural fibers like banana, palm, and hemp fibers in concrete mixes, in addition to synthetic fibers like steel and polypropylene for comparison purposes. Several mixes were tried in order to determine an optimal concrete mix that is best suited with the fibers addition. Once the optimal mix was determined, different mixes were prepared and tested where two variables were investigated: the fibers type and volume fraction, and the coarse aggregate reduction. The variables in this phase were the fibers volume fraction varied between 0.5 and 1.0% and the coarse aggregate reduction of 10 and 20% by volume of concrete. The monitoring tests were the compression test on cubes of 7 cm size, and the flexural test on beams of 5 x 5 x 20 cm size.

In Phase 1, the hemp fibers were adopted in addition to polypropylene fibers again for comparison purposes. Two variables were adopted while other factors were kept constant: the hemp fibers volume fraction and the coarse aggregate reduction. As in the trial phase, the fibers volume fraction was varied between 0.5%, 0.75%, and 1.0% associated with coarse aggregate reduction of 10%, 20%, and 30% by volume of concrete. A control mix with no fibers and no aggregate reduction was also included in the testing program. The tests performed included the compressive strength on standard cylinders (15 x 30 cm), flexure third-point load test on standard beams (15 x 15 x 53 cm), splitting tensile test on standard cylinders, modulus of elasticity on standard cylinders; in addition, the following useful tests were conducted: slump tests of the fresh concrete mixes, density at hardened state, and a thermal conductivity test. Compression and flexure tests were performed at early and late concrete age, whereas other tests were performed at only 28 days concrete age. All tests samples were prepared with 3 replicates for a better statistical representation. Consequently, a statistical analysis with 95% confidence level was also performed. Besides, analytical linear models were developed for the prediction of the compressive strength, modulus of elasticity, and flexure tests of the hemp-fiber mixes, based on the correspondent control tests data.

In the second phase, three main mixes were adopted based on Phase 1 tests results, a control mix without aggregate reduction, 0.75% hemp and 1.0% hemp mixes with 20% coarse reduction. Simply supported beams were prepared (20 x 30 x 200 cm), tested under a third-point load testing set. Different beams reinforcement types were prepared to exhibit three modes of failure: flexure, shear, and bond. The shear beams were under-reinforced with respect to shear reinforcement in order to reach a shear failure. The bond beams were prepared with minimum splice requirement in order to ensure a bond failure. Two identical beams were prepared for every concrete mix and reinforcement beam type to ensure reliability and accuracy of results.

7.2. Research Conclusions

The use of hemp fibers affects the physical and performance characteristics of concrete mixes and the following conclusions can be drawn from this research, based on the unique concrete mix adopted in this research. Note that any variation in the concrete mix proportions can always affect the relevant findings.

(1) The industrial hemp fibers perform better than banana and palm fibers when added to concrete mixes.

(2) The industrial hemp fibers need to be treated prior to their inclusion in concrete mixes, for a better bond with the surrounding matrix.

(3) The compressive strength results indicated that the cylinder tests, prepared with different fibers volumetric ratios and reductions in coarse aggregate, resulted in a decrease in the compressive strength with the increase in coarse aggregate reduction.

(4) For the flexure tests, the load-deflection curves results showed a ductile behavior of the fiber-reinforced concrete composite after the peak load is reached. The ductile behavior is directly related to the toughness of the composite material. The control specimen results showed a brittle failure of plain concrete after the peak load is reached.

(5) For the splitting tensile tests, the results indicated that the 0.75% and 1% hemp volume fractions were sufficient and adequate as an optimal substitute to the coarse reduction.

(6) The modulus of elasticity of hemp mixes showed a decrease compared with the control mix results. These results were consistent with the load-deflection curves.

(7) The thermal conductivity test showed that the presence of sufficient hemp fibers would substantially improve the thermal properties of concrete mixes, resulting in an insulating concrete.

(8) The density results of hemp mixes, as compared to that of the control mix, were less by an average of 5%.

(9) The slump test results showed that for hemp mixes, it would not be practical to go beyond 1% volumetric fraction.

(10) Comparing to the polypropylene mix results with no aggregate reduction, all hemp mixes results compared well or even better in most cases. It is not reasonable to compare hemp fibers mixes with steel fibers mixes, due to the difference in stiffness, flexible versus rigid fibers.

(11) In structural beam elements, it was commonly obseved that the hemp fibers addition resulted in a ductile behavior after the peak load is

reached. Besides, the peak loads were almost not affected while a 20% reduction in the coarse aggregates was possible.

(12) The ductile behavior was demonstrated by the larger area under the load-deflection curves in addition to the larger deflection reached after the beam failure. Moreover, based on the crack width measure at different locations on every beam type, the fibers effect was illustrated in the smaller crack width and larger number of cracks, thus a more ductile post-cracking behavior.

(13) The hemp fibers resulted in a ductile behavior for all three modes of failure flexure, shear, and bond.

(14) The potential for coarse aggregate reduction without affecting the structural performance results mitigates natural resource depletion.

In summary, hemp-reinforced concrete is a new material different from plain concrete by its lower stiffness (i.e. more flexible) better flexural ductile behavior, lower density, lower thermal conductivity, and the potential to save on coarse aggregates.

7.3. Research Recommendations

This research paved the way toward developing a sustainable concrete material produced with agricultural wastes, and a first corner stone in a promising path was founded. In order to adopt such a material in practical applications, there is a need for more research and extensive testing programs. Examples of such applications could start with pavements, shotcrete, masonry blocks, and other non-structural elements, and would end with structural applications after several materials properties have been investigated. High strength concrete, and earthquake resistant structures where ductility is required, can also be considered in future research. However, prior to any structural applications, the durability issue needs to be targeted and resolved to ensure that natural fibers do not degrade over the long term, and in this event propose viable solutions. In the current research, major physical materials tests have been investigated such as compression, flexure, splitting, and others. Other material properties and applications are proposed to be further researched such as plastic shrinkage, internal curing potential, plastering properties, durability tests such as wetting and drying and freeze and thaw tests, thin concrete sections such tiles and concrete masonry blocks as a lightweight component. Also the potential of adding lime as a partial substitute for cement needs to be investigated, since in previous research work lime was included in the mortar mixes such as in hempcrete mixes. The potential of using hemp in asphalt mixes needs also to be investigated.

Moreover, the hemp fibers must be deeply investigated, i.e. in terms of length and orientation in the concrete mix. In the current research, a length of 3 cm was fixed and it will add value to the work to study the length effect on the hemp-concrete behavior. The orientation of fibers in the specimens should also be monitored, where the process may affect the orientation (wet versus dry process).

In order to add to the experimental findings and based on the set linear models, sophisticated non-linear modeling of the new hemp-reinforced concrete mix would be required to simulate and create a representative model of the new concrete mix. In addition, finite element modeling of structural elements would provide a better simulation and representation of the new material.

For practical and industrial hemp concrete productions, the hemp production and manufacturing is important. Mechanical equipment must be used to produce equal length hemp fibers. Moreover, the processing of the fibers after soaking and drying must be mechanical, a similar machine to the one used in this research can be manufactured and used.

In conclusion, the hemp-reinforced concrete, a novel and promising material that deserves further attention and will benefit from future research in order to mature and expand. The advantages to be foreseen as a sustainable material and the social benefit it may bring are innumerable.

APPENDIX 1

SCHEMATIC VIEWS OF PHASE 2 CRACKED BEAM SPECIMENS

NOTES

Figures Legends:

F: Flexure.

S: Shear.

B: Bond.

CL: Control.

0.75%HP-20%coarse: 0.75% Hemp – 20% Coarse Aggregates

1.0%HP-20%coarse: 1.0% Hemp – 20% Coarse Aggregates.

c: is the location of crack measure.

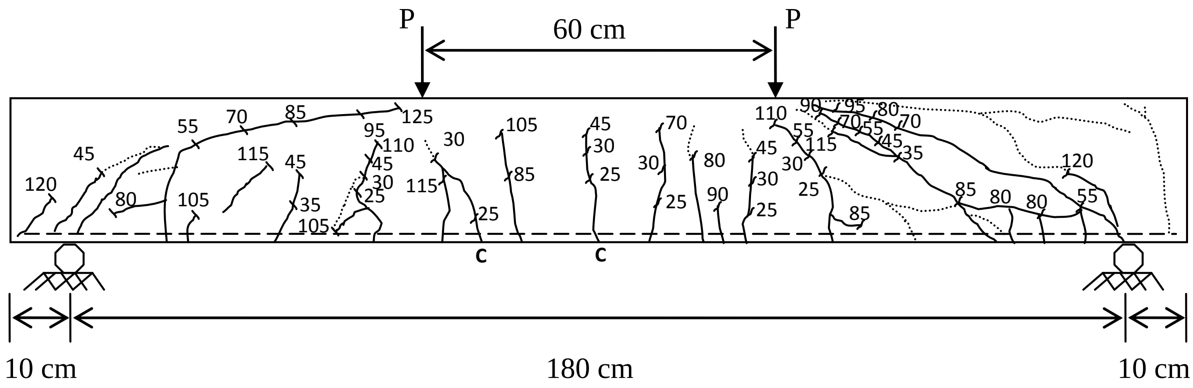


Figure A1.1. F1-CL.

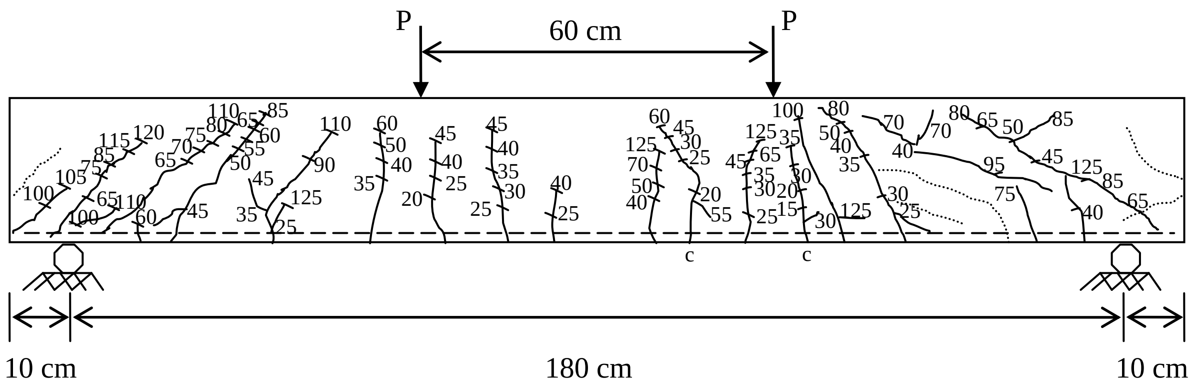


Figure A1.2. F2-CL.

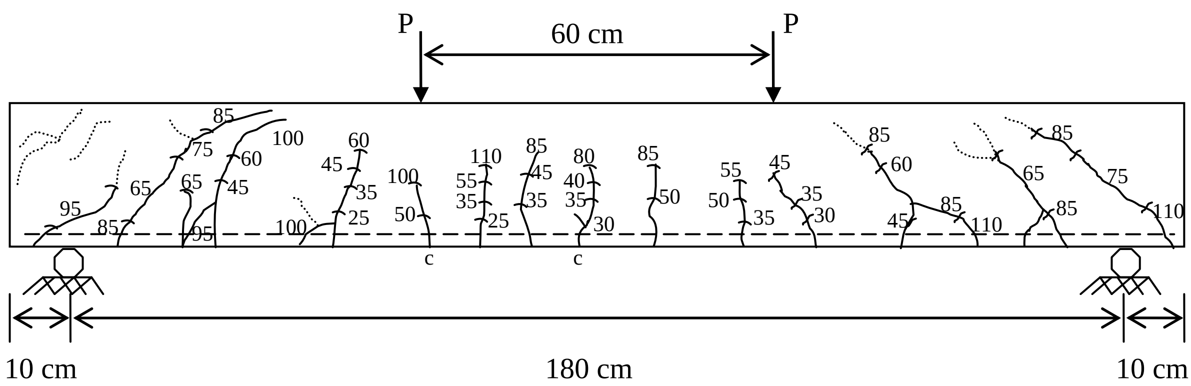


Figure A1.3. F1-0.75%HP-20%coarse.

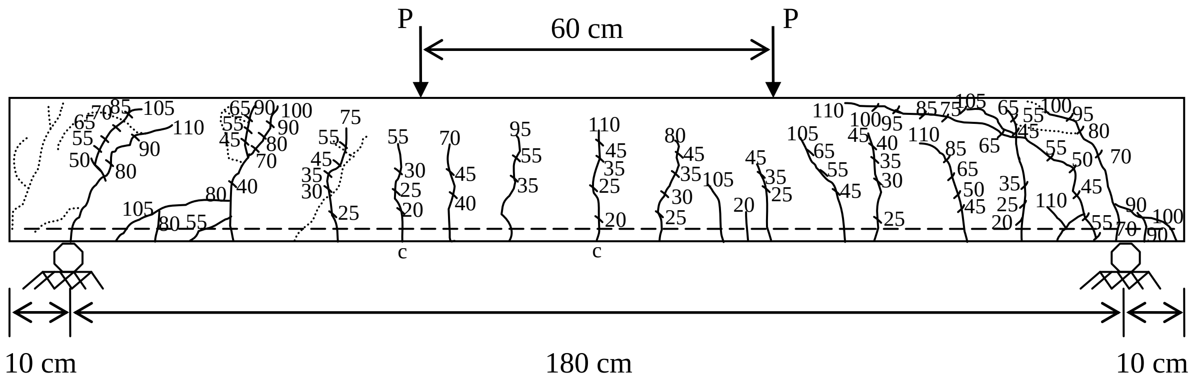


Figure A1.4. F2-0.75%HP-20%coarse.

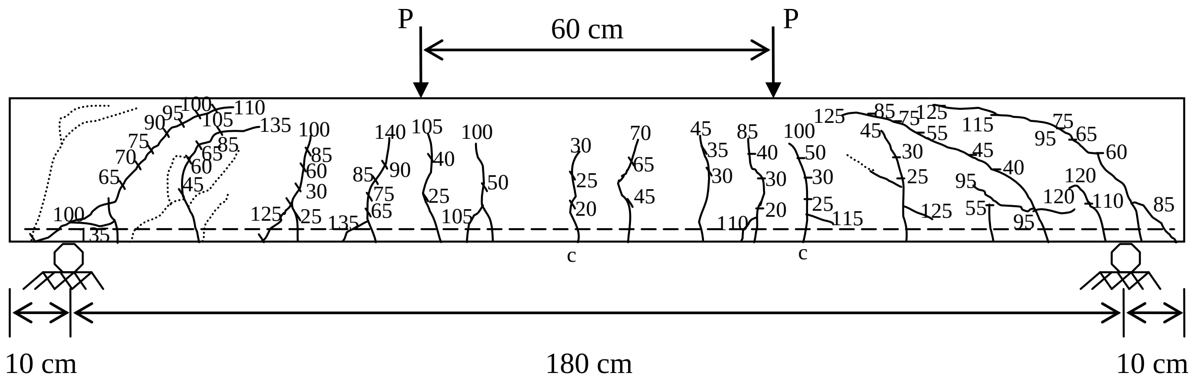


Figure A1.5. F1-1.0%HP-20%coarse.

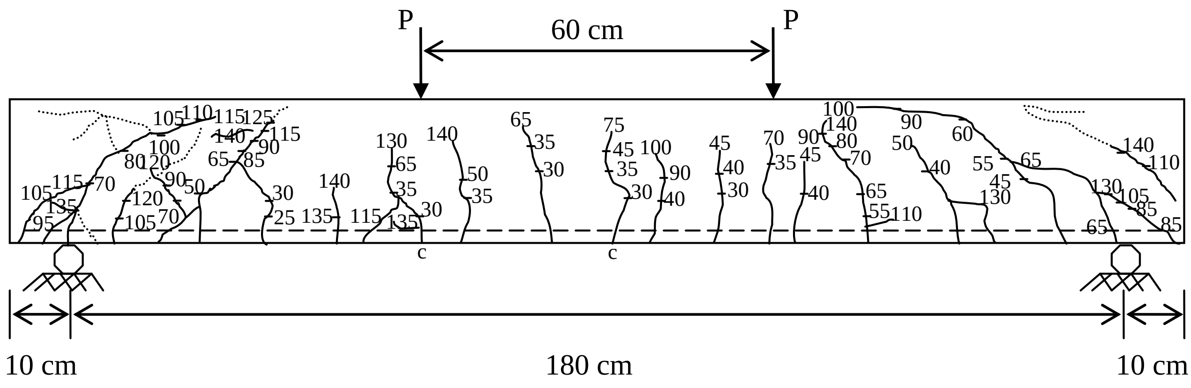


Figure A1.6. F2-1.0%HP-20%coarse

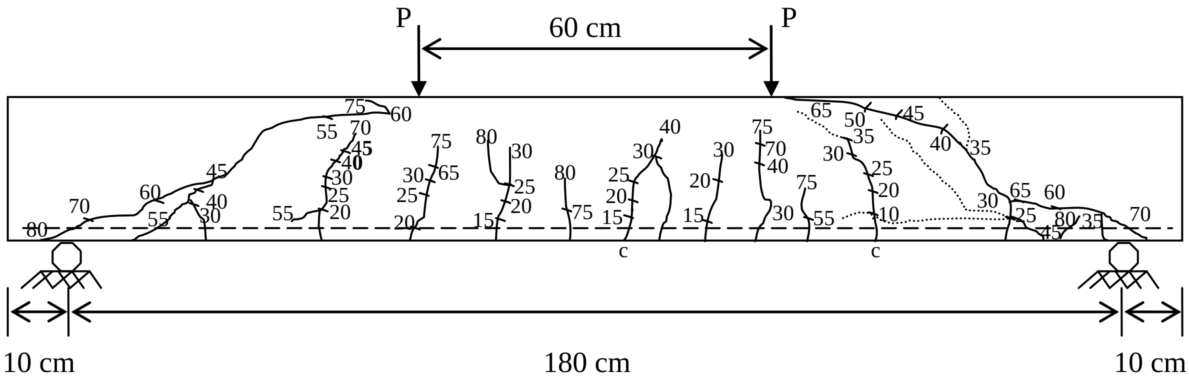


Figure A1.7. S1-CL.

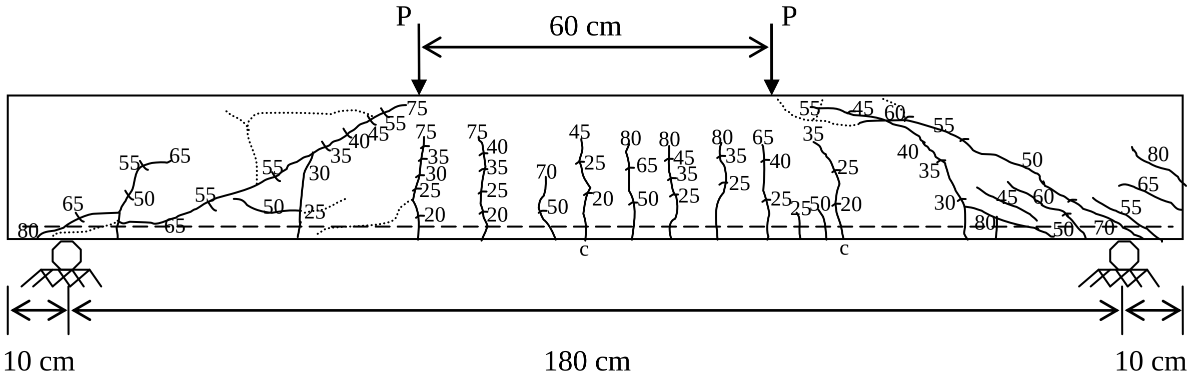


Figure A1.8. S2-CL.

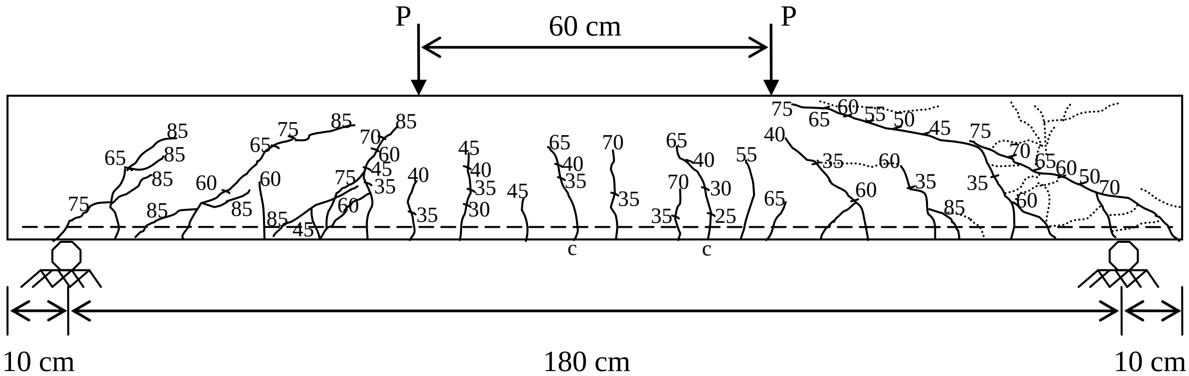


Figure A1.9. S1-0.75%HP-20%coarse.

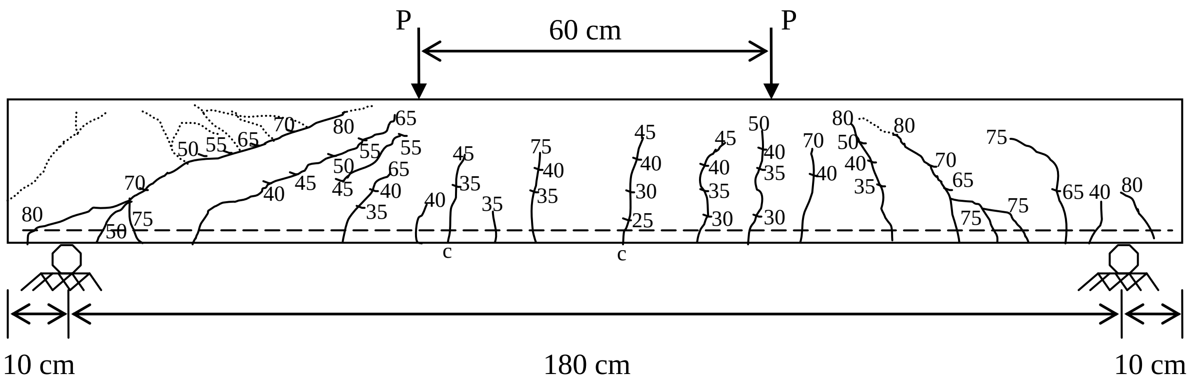


Figure A1.10. S2-0.75%HP-20%coarse

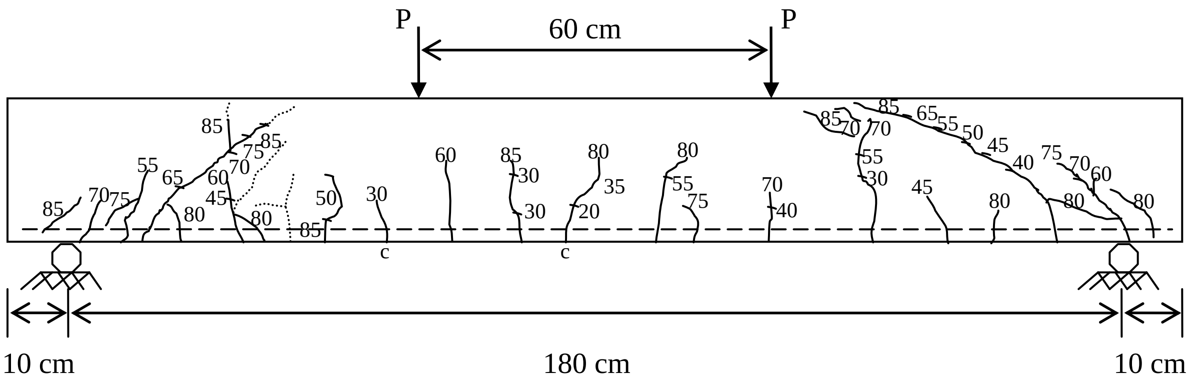


Figure A1.11. S1-1.0%HP-20%coarse

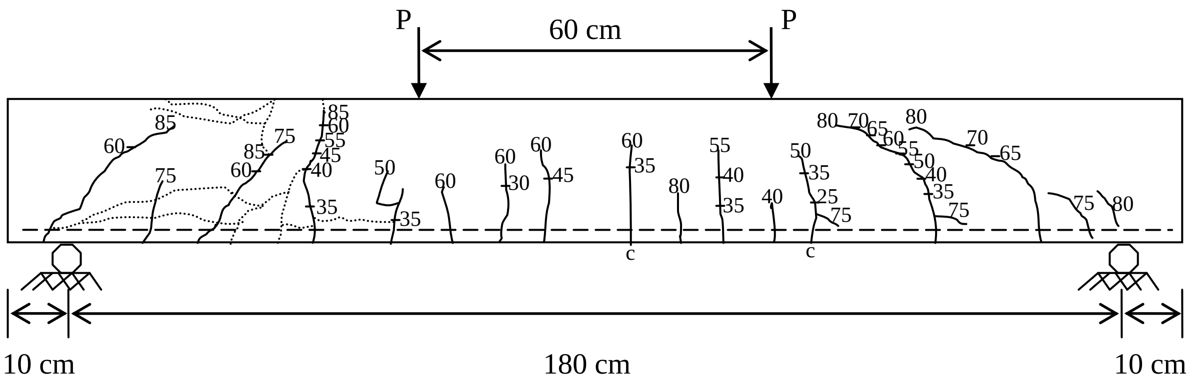


Figure A1.12. S2-1.0%HP-20%coarse.

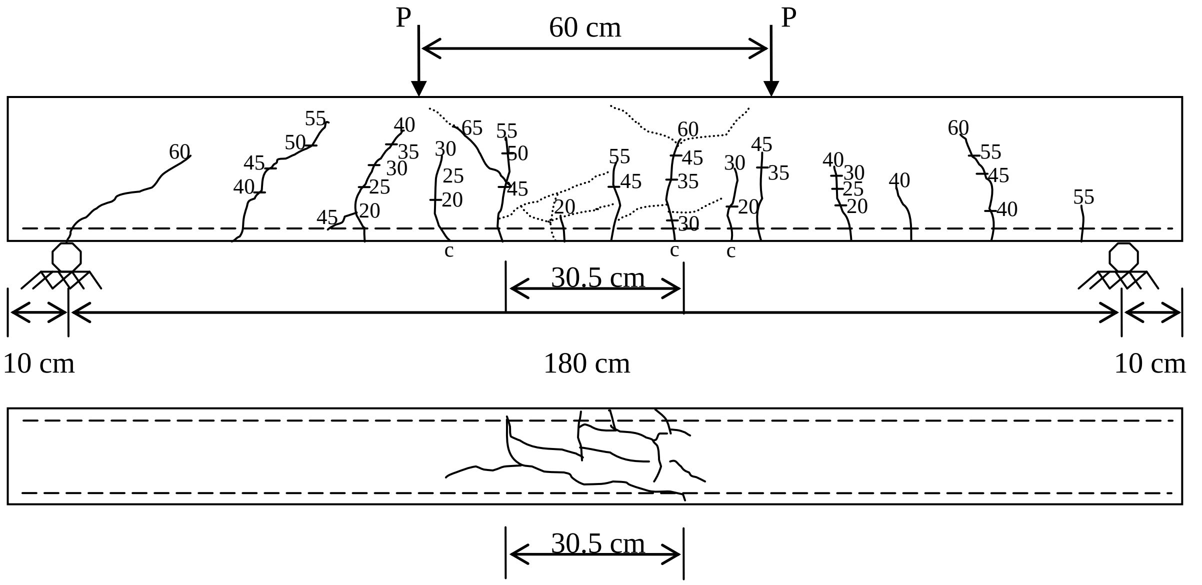


Figure A1.13. B1-CL with Bottom View

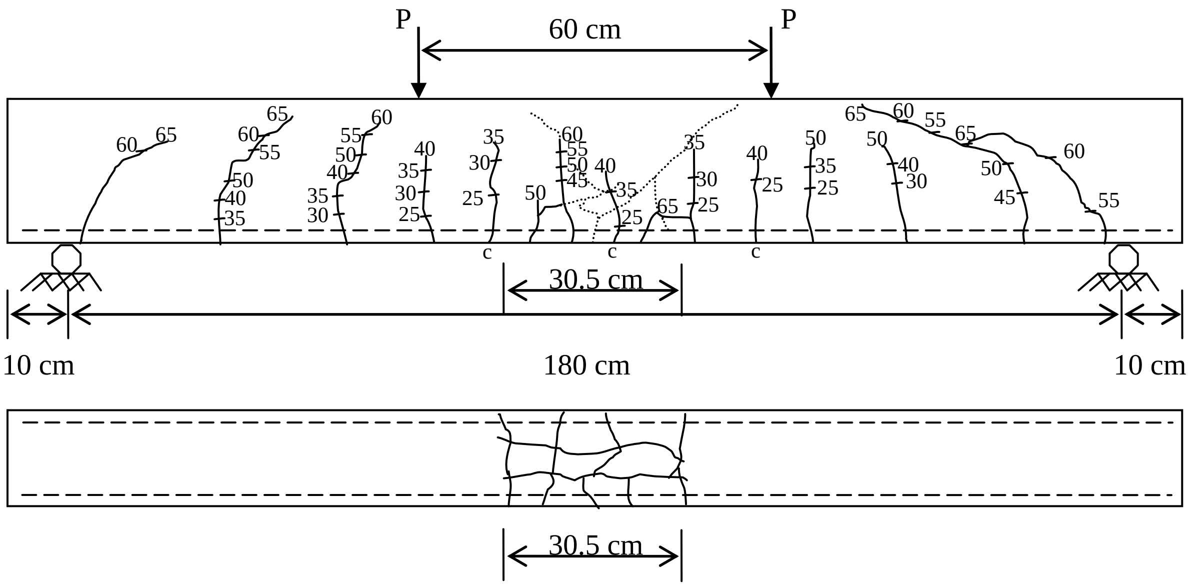


Figure A1.14. B2-CL with Bottom View.

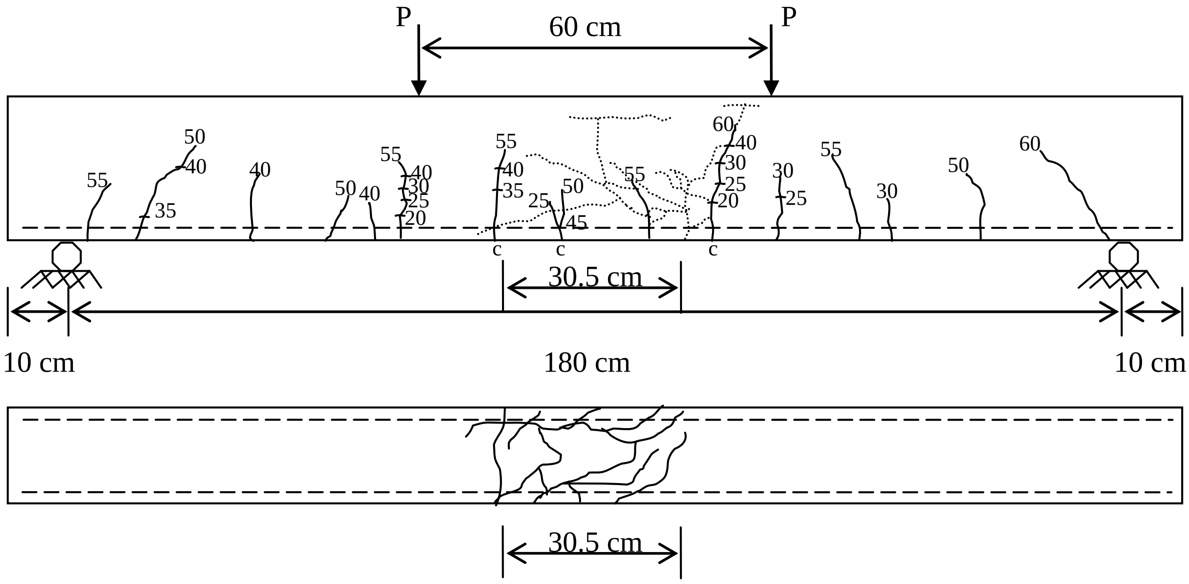


Figure A1.15. B1-0.75%HP-20%coarse (Side and Bottom View).

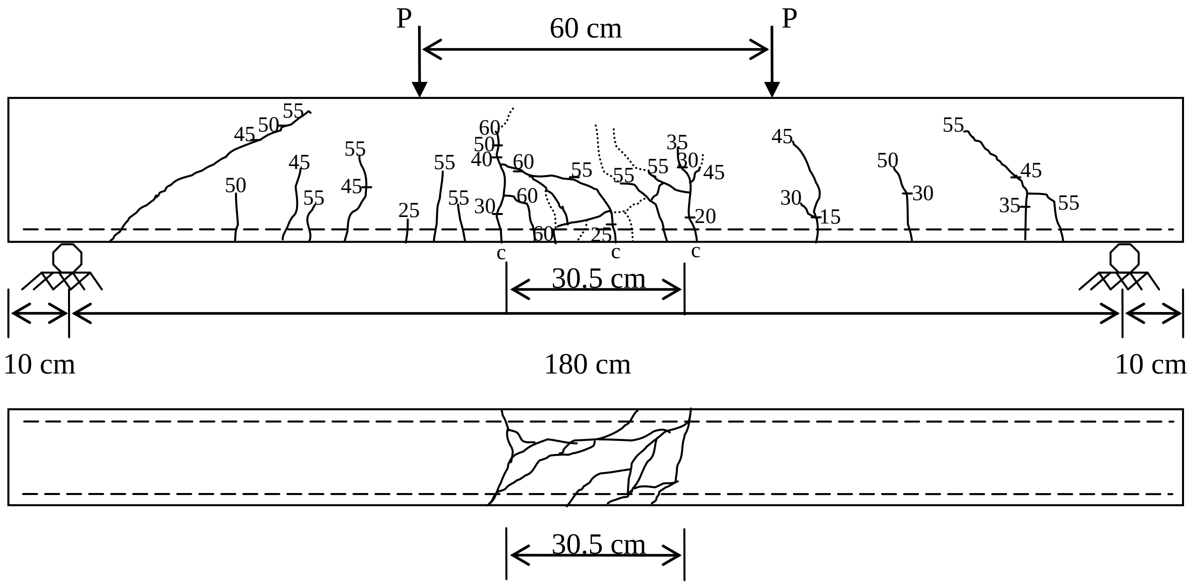


Figure A1.16. B2-0.75%HP-20%coarse (Side and Bottom View).

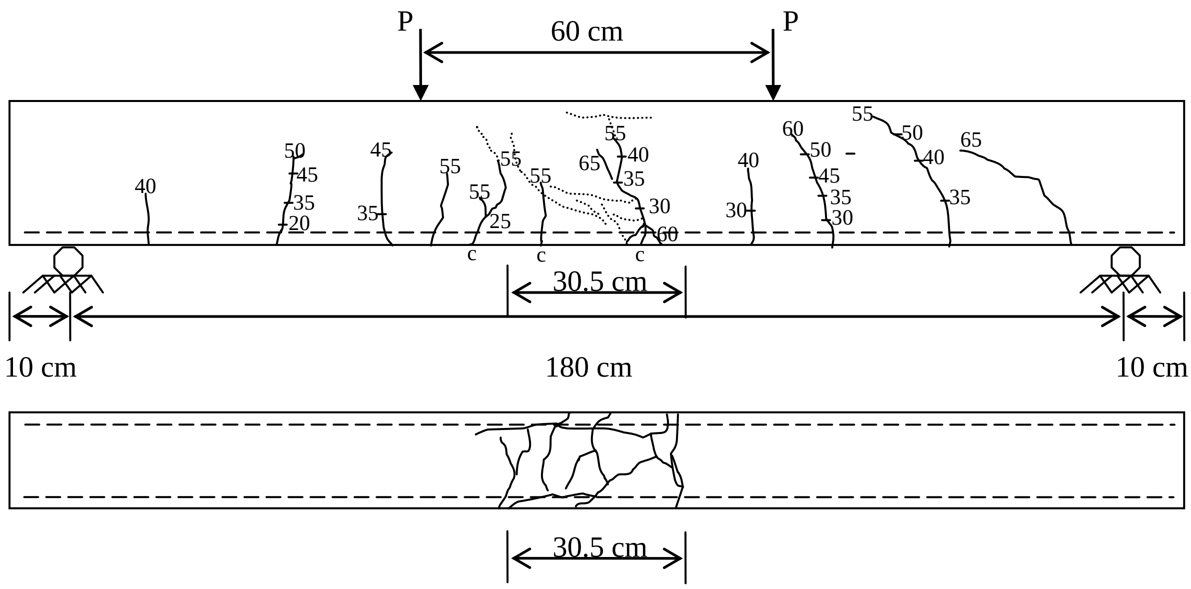


Figure A1.17. B1-1.0%HP-20%coarse (Side and Bottom View).

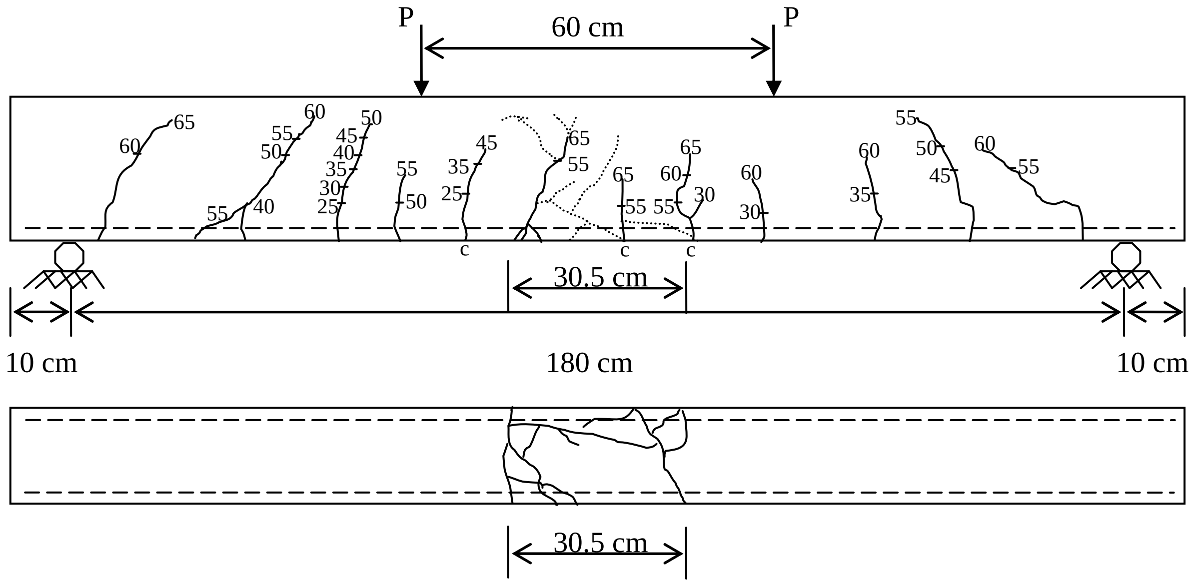


Figure A1.18. B2-1.0%HP-20%coarse (Side and Bottom View).

APPENDIX 2

DATA FOR LOAD-DEFLECTION CURVES OF ALL PHASES

Table A2.1. Flexure Tests Data for Trial Mix: Control 1, at 10 Days.

Control 1					
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.015	0.000	0.606	0.214	1.785	0.288
0.015	0.007	0.629	0.221	1.827	0.288
0.019	0.015	0.649	0.229	1.865	0.288
0.023	0.022	0.653	0.236	1.904	0.288
0.031	0.030	0.679	0.244	1.942	0.288
0.035	0.037	0.706	0.244	1.977	0.288
0.038	0.044	0.733	0.244	2.019	0.288
0.046	0.052	0.756	0.244	2.057	0.288
0.054	0.059	0.779	0.244	2.096	0.288
0.065	0.066	0.802	0.244	2.134	0.288
0.073	0.074	0.825	0.244	2.176	0.288
0.081	0.074	0.844	0.244	2.215	0.288
0.092	0.081	0.787	0.251	2.253	0.288
0.100	0.089	0.821	0.251	2.295	0.288
0.107	0.096	0.844	0.251	2.334	0.288
0.119	0.103	0.829	0.251	2.376	0.288
0.131	0.111	0.864	0.251	2.418	0.288
0.142	0.111	0.898	0.251	2.460	0.288
0.154	0.118	0.925	0.251	2.503	0.288
0.165	0.125	0.956	0.258	2.541	0.288
0.177	0.125	0.979	0.266	2.583	0.288
0.188	0.133	1.006	0.273	2.629	0.288
0.203	0.140	1.021	0.273	2.672	0.288
0.215	0.148	1.048	0.273	2.718	0.288
0.230	0.148	1.075	0.273	2.760	0.288
0.246	0.148	1.105	0.273	2.806	0.288
0.257	0.155	1.136	0.273	2.852	0.288
0.273	0.155	1.171	0.273	2.898	0.288
0.288	0.162	1.205	0.273	2.944	0.288
0.303	0.170	1.240	0.273	2.990	0.288
0.319	0.170	1.271	0.273	3.036	0.288
0.338	0.177	1.301	0.281	3.078	0.288
0.353	0.177	1.332	0.288	3.124	0.288
0.368	0.185	1.366	0.288	3.171	0.288
0.388	0.185	1.401	0.288	3.217	0.288
0.407	0.185	1.432	0.288	3.267	0.288
0.426	0.192	1.470	0.288	3.313	0.288
0.441	0.192	1.505	0.288	3.355	0.288
0.464	0.199	1.539	0.288	3.405	0.288
0.484	0.199	1.574	0.288	3.451	0.288
0.503	0.199	1.608	0.288	3.501	0.288
0.522	0.199	1.643	0.288	3.551	0.288
0.541	0.199	1.681	0.288	3.585	0.288
0.560	0.207	1.716	0.288		
0.583	0.207	1.750	0.288		

Table A2.2. Flexure Tests Data for Trial Mix: Control 2, at 10 Days.

Control 2					
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**Mm**
0.004	0.000	0.725	0.502	2.126	0.679
0.012	0.022	0.752	0.509	2.169	0.679
0.019	0.030	0.756	0.517	2.211	0.679
0.031	0.044	0.779	0.517	2.257	0.679
0.038	0.059	0.810	0.524	2.299	0.679
0.050	0.074	0.841	0.531	2.349	0.679
0.061	0.089	0.871	0.539	2.391	0.679
0.069	0.103	0.906	0.546	2.437	0.679
0.081	0.118	0.937	0.546	2.483	0.686
0.092	0.133	0.971	0.554	2.530	0.686
0.104	0.148	1.002	0.561	2.576	0.686
0.115	0.155	1.036	0.568	2.622	0.694
0.131	0.170	1.071	0.576	2.672	0.701
0.142	0.185	1.105	0.576	2.718	0.701
0.157	0.192	1.136	0.583	2.764	0.701
0.173	0.199	1.171	0.591	2.810	0.701
0.188	0.214	1.209	0.598	2.860	0.701
0.207	0.221	1.240	0.598	2.910	0.701
0.223	0.229	1.278	0.605	2.956	0.701
0.242	0.236	1.313	0.605	3.006	0.709
0.261	0.244	1.351	0.613	3.055	0.709
0.284	0.251	1.390	0.620	3.105	0.709
0.299	0.258	1.424	0.620	3.155	0.709
0.322	0.273	1.462	0.627	3.205	0.709
0.342	0.281	1.501	0.627	3.251	0.709
0.365	0.288	1.539	0.635		
0.388	0.295	1.578	0.635		
0.411	0.303	1.616	0.635		
0.434	0.317	1.654	0.642		
0.457	0.317	1.689	0.642		
0.484	0.332	1.720	0.642		
0.507	0.340	1.447	0.642		
0.507	0.391	1.509	0.642		
0.537	0.406	1.566	0.642		
0.560	0.421	1.624	0.642		
0.576	0.428	1.677	0.650		
0.591	0.443	1.731	0.650		
0.603	0.450	1.777	0.650		
0.610	0.465	1.823	0.657		
0.626	0.472	1.869	0.657		
0.637	0.480	1.912	0.657		
0.645	0.480	1.954	0.657		
0.660	0.487	1.996	0.664		
0.683	0.487	2.038	0.672		
0.706	0.495	2.080	0.679		

Table A2.3. Flexure Tests Data for Trial Mix: Control 3, at 10 Days.

Control 3					
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**Mm**
0.015	0.000	0.802	0.303	2.173	0.591
0.019	0.000	0.702	0.310	2.219	0.598
0.019	0.007	0.722	0.310	2.265	0.598
0.019	0.015	0.756	0.317	2.315	0.613
0.019	0.022	0.783	0.317	2.364	0.613
0.015	0.030	0.810	0.325	2.414	0.620
0.019	0.037	0.848	0.325	2.464	0.627
0.027	0.044	0.883	0.332	2.510	0.635
0.027	0.052	0.917	0.340	2.556	0.642
0.019	0.059	0.952	0.347	2.606	0.650
0.023	0.066	0.990	0.354	2.656	0.650
0.027	0.074	1.025	0.362	2.710	0.657
0.027	0.081	1.063	0.362	2.764	0.664
0.031	0.081	1.102	0.376	2.810	0.672
0.035	0.089	1.136	0.376	2.863	0.679
0.042	0.103	1.171	0.384	2.913	0.679
0.050	0.111	1.205	0.399	2.971	0.694
0.061	0.118	1.244	0.406	3.025	0.694
0.077	0.125	1.278	0.413	3.082	0.701
0.088	0.133	1.313	0.421	3.140	0.709
0.107	0.140	1.347	0.428	3.194	0.709
0.127	0.148	1.378	0.443	3.255	0.716
0.142	0.155	1.413	0.443	3.313	0.723
0.169	0.162	1.439	0.450	3.374	0.723
0.188	0.162	1.144	0.458	3.435	0.731
0.211	0.170	1.213	0.458	3.497	0.738
0.242	0.177	1.274	0.465	3.554	0.746
0.269	0.185	1.332	0.465	3.612	0.746
0.296	0.192	1.390	0.472	3.673	0.753
0.326	0.199	1.447	0.480	3.739	0.760
0.353	0.207	1.493	0.480	3.800	0.760
0.388	0.207	1.539	0.487	3.861	0.768
0.418	0.214	1.581	0.495	3.923	0.768
0.445	0.221	1.624	0.502	3.984	0.775
0.480	0.229	1.666	0.517	4.042	0.782
0.507	0.236	1.708	0.517	4.103	0.782
0.537	0.244	1.754	0.532	4.165	0.790
0.572	0.244	1.800	0.539		
0.606	0.251	1.842	0.539		
0.637	0.258	1.889	0.546		
0.668	0.266	1.931	0.561		
0.699	0.273	1.977	0.561		
0.725	0.281	2.023	0.568		
0.752	0.288	2.073	0.576		
0.779	0.295	2.123	0.583		

Table A2.4. Flexure Tests Data for Trial Mixes: All 0.5% Hemp, at 10 Days.

0.5%Hemp		0.5%Hemp-10%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**
0.004	0.000	0.004	0.000
1.033	0.443	0.104	0.125
2.015	0.627	0.495	0.214
2.683	0.694	1.013	0.325
2.457	0.709	1.501	0.413
2.610	0.723	2.031	0.480
2.925	0.760	2.602	0.509
2.418	0.819	1.992	0.591
1.988	0.871	1.512	0.664
1.090	1.026	1.094	0.723
0.702	1.144	0.507	0.937
0.353	1.351	0.196	1.240
0.203	1.469	0.196	1.307
0.100	1.580	0.215	1.343
0.088	1.609	0.069	1.904

0.5%Hemp-20%coarse		0.5%Local Hemp	
2P (kN)	**mm**	**2P (kN)**	**mm**
0.004	0.000	0.004	0.000
0.522	0.170	0.626	0.096
1.017	0.303	1.052	0.155
1.570	0.354	0.944	0.162
2.088	0.399	1.662	0.214
2.495	0.413	2.668	0.288
2.096	0.436	3.405	0.317
2.265	0.458	3.766	0.332
2.092	0.495	2.986	0.376
1.597	0.591	3.401	0.406
1.604	0.598	3.723	0.472
1.098	0.701	3.696	0.495
0.587	0.878	3.704	0.524
0.457	0.967	3.048	0.716
0.461	0.974	2.000	0.856
0.246	1.144	1.524	1.211
0.265	1.188	0.990	1.565
0.257	1.203	0.499	2.229
0.265	1.225	0.503	2.458
0.238	1.284	0.426	2.598
0.253	1.299		
0.188	1.462		

Table A2.5. Flexure Tests Data for Trial Mixes: All 0.75 and 1% Hemp, at 10 Days.

0.75%Hemp-20%coarse	
2P (kN)	**mm**
0.031	0.000
0.503	0.207
1.025	0.310
1.654	0.354
2.096	0.428
3.048	0.487
3.931	0.546
3.063	0.620
3.516	0.635
4.003	0.657
4.088	0.657
3.504	0.701
3.029	0.738
2.483	0.797
1.996	0.878
1.505	0.960
1.098	1.033
0.564	1.196
0.292	1.439

1%Hemp-20%coarse	
2P (kN)	**mm**
0.000	0.000
0.501	0.116
1.015	0.186
1.502	0.249
2.068	0.341
3.027	0.522
3.352	0.590
2.640	0.650
3.005	0.664
3.595	0.788
3.650	0.838
3.003	0.880
2.542	0.954
1.999	1.072
1.501	1.219
0.998	1.321
0.509	1.506
0.177	1.759

0.75%Hemp	
2P (kN)	**mm**
0.031	0.000
0.599	0.192
1.090	0.384
1.562	0.502
2.065	0.591
2.579	0.672
3.029	0.746
3.481	0.812
2.672	0.827
2.917	0.849
3.144	0.878
2.530	0.908
2.007	0.960
1.558	1.041
1.205	1.129
1.159	1.152
1.178	1.166
1.094	1.196
0.514	1.403
0.276	1.469
0.180	1.624

Table A2.6. Flexure Tests Data for Trial Mixes: All Palm, at 10 Days.

0.5%Palm	
2P (kN)	**mm**
0.004	0.000
0.487	0.185
1.025	0.295
1.528	0.340
2.011	0.362
2.507	0.384
2.553	0.384
3.044	0.406
3.240	0.413
0.522	0.502
0.296	0.539
0.196	0.568
0.100	0.901

0.5%Palm-20%coarse	
2P (kN)	**mm**
0.008	0.000
0.507	0.155
1.029	0.266
1.524	0.317
2.023	0.340
2.545	0.347
3.013	0.369
3.574	0.384
1.693	0.435
1.063	0.480
0.603	0.591
0.307	0.864
0.196	0.952

0.5%Palm-10%coarse	
2P (kN)	**mm**
0.004	0.000
0.507	0.288
1.025	0.325
1.478	0.347
2.027	0.362
2.514	0.362
3.032	0.362
3.347	0.362
2.215	0.376
1.555	0.487
1.094	0.598
0.699	0.952
0.495	1.698
0.545	1.720
0.549	1.735
0.545	1.742
0.541	1.742
0.549	1.749
0.560	1.764
0.576	1.764
0.545	1.786
0.526	1.801
0.549	1.808
0.449	1.875
0.472	1.912
0.457	1.934
0.484	1.993
0.476	2.000

1%Palm	
2P (kN)	**mm**
0.027	0.000
0.503	0.214
1.013	0.362
1.562	0.517
2.011	0.605
2.545	0.657
3.021	0.686
3.589	0.716
3.861	0.731
2.134	0.797
1.992	0.797
2.000	0.805
2.023	0.819
1.532	0.871
1.094	1.041
0.994	1.100
1.002	1.144
0.795	1.425
0.806	1.432
0.798	1.447
0.833	1.484
0.821	1.484
0.537	1.646
0.841	1.742
0.748	1.786
0.825	1.816
0.940	1.882
0.595	2.141
0.722	2.200
0.576	2.384

Table A2.7. Flexure Tests Data for Trial Mixes: Banana, Steel, and Polypropylene, at 10 Days.

1%Banana		0.5%Steel		1%Polypropylene	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.012	0.000	0.012	0.000	0.038	0.000
0.507	0.531	1.013	0.125	0.154	0.118
0.679	0.635	2.042	0.170	0.311	0.177
0.487	0.664	3.002	0.192	0.610	0.317
1.002	0.790	3.938	0.221	0.917	0.376
1.524	0.842	3.178	0.258	1.213	0.436
2.034	0.871	3.700	0.288	1.804	0.472
2.518	0.908	4.003	0.303	2.111	0.517
3.006	0.945	4.499	0.369	2.514	0.635
3.577	0.960	4.345	0.391	2.910	0.709
4.053	0.974	4.606	0.450	3.551	0.790
4.575	0.982	4.871	0.613	3.846	0.819
0.441	1.203	4.529	0.701	3.347	0.834
0.975	1.314	4.602	0.731	2.986	0.871
0.894	1.580	4.015	0.797	3.313	0.901
0.902	1.609	2.568	0.923	3.616	0.937
0.495	2.835	2.483	0.967	3.812	1.011
0.687	3.056	2.679	1.026	3.804	1.056
0.595	3.086	2.579	1.048	3.600	1.093
0.645	3.122	2.610	1.063	3.520	1.100
0.495	3.255	2.138	1.107	3.608	1.129
0.518	3.337	2.261	1.122	3.731	1.159
0.203	3.587	2.031	1.144	3.627	1.196
0.234	3.654	1.013	1.247	3.735	1.233
		0.879	1.314	3.719	1.248
		0.971	1.358	3.754	1.270
		0.637	1.528	3.458	1.307
		0.691	1.565	3.470	1.336
		0.680	1.572	3.428	1.358
		0.641	1.602	3.562	1.380
				3.577	1.395
				3.178	1.484
				3.182	1.491
				2.906	1.535
				2.787	1.572
				2.906	1.624
				2.299	1.757
				2.668	1.919
				2.675	1.919

Table A2.8. Flexure Tests Data for Trial Mixes: Control 1, at 28 Days.

Control							
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.038	0.000	0.368	0.258	1.059	0.399	2.499	0.480
0.042	0.007	0.384	0.266	1.086	0.399	2.541	0.480
0.042	0.015	0.399	0.273	1.117	0.399	2.579	0.480
0.042	0.022	0.415	0.273	1.148	0.406	2.625	0.480
0.042	0.030	0.426	0.273	1.175	0.406	2.672	0.487
0.046	0.037	0.441	0.273	1.205	0.406	2.714	0.487
0.046	0.044	0.457	0.280	1.228	0.406	2.760	0.487
0.050	0.052	0.472	0.280	1.259	0.406	2.806	0.495
0.058	0.059	0.487	0.280	1.290	0.406	2.852	0.495
0.061	0.066	0.503	0.288	1.324	0.413	2.898	0.495
0.069	0.074	0.522	0.288	1.355	0.413	2.944	0.502
0.073	0.081	0.541	0.295	1.382	0.413	2.994	0.509
0.081	0.081	0.557	0.295	1.413	0.413	3.040	0.517
0.084	0.089	0.576	0.295	1.447	0.421	3.090	0.517
0.092	0.096	0.591	0.303	1.485	0.421	3.136	0.517
0.100	0.103	0.610	0.303	1.512	0.421	3.182	0.524
0.107	0.111	0.626	0.303	1.543	0.428	3.228	0.524
0.111	0.111	0.645	0.303	1.581	0.428	3.278	0.524
0.123	0.118	0.660	0.310	1.612	0.428	3.328	0.531
0.127	0.125	0.679	0.310	1.647	0.428	3.378	0.531
0.134	0.133	0.660	0.347	1.681	0.428	3.432	0.531
0.142	0.133	0.691	0.347	1.716	0.436	3.481	0.531
0.154	0.148	0.714	0.354	1.750	0.436	3.531	0.539
0.161	0.148	0.737	0.354	1.789	0.436	3.585	0.539
0.169	0.155	0.756	0.354	1.823	0.443	3.639	0.539
0.180	0.162	0.779	0.354	1.862	0.443	3.689	0.539
0.188	0.170	0.795	0.362	1.900	0.443	3.742	0.539
0.196	0.177	0.779	0.362	1.938	0.450	3.796	0.546
0.207	0.185	0.772	0.369	1.973	0.450	3.846	0.546
0.219	0.185	0.795	0.376	2.011	0.450	3.957	0.546
0.226	0.192	0.821	0.376	2.050	0.458	4.011	0.554
0.238	0.199	0.844	0.376	2.088	0.458	4.069	0.554
0.253	0.207	0.871	0.376	2.126	0.458	4.122	0.561
0.261	0.214	0.894	0.376	2.165	0.458	4.180	0.568
0.276	0.214	0.917	0.384	2.207	0.465	4.288	0.568
0.288	0.229	0.940	0.384	2.245	0.465	4.349	0.568
0.299	0.229	0.963	0.384	2.288	0.472	4.407	0.576
0.315	0.236	0.986	0.391	2.330	0.472	4.464	0.576
0.326	0.244	0.963	0.391	2.368	0.472	4.518	0.576
0.342	0.244	1.002	0.391	2.414	0.472	4.575	0.576
0.357	0.258	1.033	0.391	2.457	0.480	4.633	0.576

Table A2.9. Flexure Tests Data for Trial Mixes: Control 2, at 28 Days.

Control							
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.004	0.000	0.111	0.517	0.499	0.797	1.639	0.923
0.008	0.007	0.119	0.517	0.518	0.805	1.681	0.930
0.015	0.015	0.134	0.524	0.526	0.805	1.723	0.930
0.019	0.022	0.150	0.531	0.534	0.805	1.766	0.937
0.023	0.030	0.157	0.531	0.557	0.805	1.808	0.937
0.031	0.037	0.165	0.539	0.576	0.805	1.858	0.937
0.038	0.052	0.173	0.539	0.599	0.805	1.900	0.937
0.046	0.066	0.188	0.554	0.618	0.812	1.946	0.945
0.054	0.074	0.200	0.554	0.649	0.812	1.992	0.945
0.061	0.096	0.215	0.561	0.687	0.812	2.038	0.945
0.069	0.111	0.223	0.568	0.718	0.819	2.084	0.945
0.077	0.125	0.230	0.576	0.748	0.819	2.134	0.952
0.088	0.140	0.242	0.583	0.737	0.841	2.176	0.960
0.100	0.155	0.257	0.583	0.775	0.849	2.226	0.960
0.107	0.177	0.230	0.591	0.814	0.849	2.276	0.960
0.119	0.192	0.250	0.591	0.848	0.849	2.326	0.967
0.134	0.207	0.257	0.598	0.879	0.849	2.380	0.967
0.146	0.214	0.273	0.605	0.914	0.856	2.437	0.967
0.157	0.229	0.288	0.605	0.948	0.856	2.491	0.967
0.169	0.244	0.303	0.620	0.983	0.856	2.541	0.967
0.180	0.251	0.319	0.627	1.021	0.856	2.595	0.967
0.196	0.266	0.338	0.635	1.056	0.864	2.652	0.967
0.203	0.273	0.334	0.635	1.090	0.864	2.710	0.967
0.211	0.280	0.349	0.642	1.125	0.864	2.768	0.974
0.219	0.288	0.368	0.650	1.155	0.864	2.825	0.974
0.226	0.303	0.388	0.657	1.186	0.864	2.883	0.974
0.242	0.310	0.415	0.657	1.213	0.871	2.940	0.974
0.246	0.317	0.434	0.657	1.152	0.878	2.998	0.974
0.246	0.325	0.395	0.686	1.201	0.886	3.055	0.974
0.226	0.332	0.399	0.701	1.247	0.886	3.117	0.974
0.223	0.332	0.361	0.723	1.282	0.886	3.178	0.974
0.230	0.340	0.380	0.738	1.213	0.901	3.236	0.982
0.246	0.347	0.395	0.746	1.267	0.908	3.297	0.982
0.253	0.354	0.407	0.753	1.313	0.908	3.359	0.982
0.269	0.369	0.384	0.775	1.355	0.908	3.673	0.982
0.284	0.369	0.415	0.782	1.393	0.908	3.735	0.982
0.296	0.384	0.438	0.790	1.432	0.915	3.800	0.982
0.307	0.399	0.468	0.790	1.474	0.915	3.861	0.982
0.315	0.413	0.476	0.797	1.512	0.915	3.931	0.989
0.123	0.502	0.487	0.797	1.555	0.923	4.119	0.989
0.134	0.509	0.507	0.797	1.597	0.923	4.633	0.989

Table A2.10. Flexure Tests Data for Trial Mixes: Control 3, at 28 Days.

Control							
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.031	0.000	0.184	0.295	0.702	0.620	1.658	0.842
0.035	0.000	0.188	0.303	0.725	0.620	1.689	0.849
0.035	0.000	0.200	0.310	0.745	0.635	1.727	0.856
0.035	0.000	0.211	0.317	0.768	0.635	1.754	0.864
0.035	0.007	0.223	0.325	0.787	0.650	1.827	0.871
0.035	0.007	0.230	0.332	0.718	0.650	1.900	0.878
0.035	0.015	0.238	0.340	0.729	0.650	1.935	0.893
0.035	0.022	0.253	0.347	0.718	0.650	1.973	0.893
0.035	0.030	0.265	0.354	0.722	0.650	2.007	0.901
0.031	0.037	0.280	0.362	0.737	0.650	2.042	0.908
0.031	0.044	0.292	0.369	0.764	0.657	2.080	0.908
0.031	0.044	0.307	0.384	0.795	0.664	2.119	0.915
0.031	0.052	0.319	0.391	0.829	0.664	2.157	0.923
0.035	0.059	0.334	0.399	0.856	0.672	2.234	0.930
0.035	0.066	0.349	0.406	0.879	0.679	2.272	0.937
0.035	0.074	0.361	0.413	0.906	0.686	2.315	0.945
0.035	0.074	0.380	0.421	0.933	0.686	2.391	0.952
0.035	0.081	0.395	0.436	0.960	0.694	2.430	0.960
0.035	0.096	0.403	0.443	0.983	0.701	2.472	0.967
0.035	0.103	0.418	0.450	1.006	0.709	2.510	0.967
0.038	0.111	0.430	0.458	1.033	0.716	2.553	0.974
0.042	0.125	0.441	0.465	1.056	0.723	2.595	0.982
0.050	0.140	0.457	0.480	1.082	0.731	2.633	0.989
0.054	0.148	0.468	0.495	1.109	0.738	2.675	0.997
0.054	0.155	0.480	0.502	1.136	0.746	2.714	0.997
0.058	0.162	0.495	0.517	1.163	0.753	2.760	1.004
0.065	0.177	0.507	0.531	1.194	0.760	2.802	1.011
0.073	0.185	0.514	0.546	1.221	0.760	2.894	1.019
0.077	0.199	0.530	0.554	1.251	0.768	2.940	1.026
0.084	0.207	0.537	0.561	1.282	0.775	2.982	1.033
0.092	0.214	0.549	0.568	1.313	0.782	3.025	1.041
0.096	0.221	0.564	0.576	1.343	0.790	3.117	1.048
0.104	0.236	0.576	0.583	1.370	0.790	3.163	1.056
0.115	0.236	0.591	0.583	1.401	0.797	3.205	1.063
0.123	0.251	0.603	0.591	1.432	0.805	3.255	1.063
0.131	0.251	0.618	0.598	1.459	0.812	3.297	1.070
0.142	0.258	0.626	0.598	1.493	0.812	3.347	1.078
0.146	0.266	0.641	0.605	1.524	0.819	3.439	1.085
0.157	0.273	0.656	0.605	1.558	0.827	3.539	1.092
0.165	0.280	0.672	0.613	1.589	0.834	3.581	1.100
0.173	0.288	0.683	0.613	1.620	0.842	3.631	1.107

Table A2.11. Flexure Tests Data for Trial Mixes: All 0.5% Hemp, at 28 Days.

0.5%Hemp		0.5%Hemp-10%coarse		0.5%Hemp-20%coasre	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.027	0.000	0.004	0.000	0.008	0.000
0.595	0.303	0.683	0.266	0.603	0.325
1.198	0.391	1.209	0.480	1.443	0.480
1.793	0.458	1.762	0.650	2.576	0.650
3.693	0.583	2.361	0.731	3.355	0.709
2.986	0.598	3.006	0.797	3.009	0.716
3.685	0.627	3.746	0.849	3.608	0.746
2.967	0.694	2.829	0.908	2.007	0.856
2.042	0.760	3.032	0.960	1.355	0.997
1.390	0.842	1.988	1.115	0.760	1.462
0.887	0.945	1.405	1.247	0.407	1.742
0.372	1.211	0.956	1.417	0.107	2.200
0.088	2.325	0.511	1.653		
		0.257	1.912		
		0.165	2.200		

0.5%-Local Hemp	
2P (kN)	**mm**
0.096	0.000
0.530	0.111
1.082	0.199
1.566	0.340
2.368	0.428
3.090	0.487
3.758	0.539
4.533	0.598
4.679	0.605
3.597	0.686
4.069	0.709
4.522	0.738
4.564	0.746
4.096	0.775
3.574	0.812
3.535	0.812
3.002	0.856
2.403	0.945
2.000	1.026
1.370	1.152
0.998	1.307
1.017	1.321
0.503	1.624
0.161	2.230

Table A2.12. Flexure Tests Data for Trial Mixes: All 0.75 and 1% Hemp, at 28 Days.

0.75%Hemp		0.75%Hemp-20%coarse		1%Hemp-20%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0.031	0.000	0.002	0.000	0.000	0.000
0.503	0.221	0.696	0.237	0.743	0.321
1.010	0.244	1.252	0.282	1.105	0.487
0.891	0.266	2.192	0.320	2.084	0.542
1.528	0.303	3.072	0.362	3.029	0.606
2.130	0.340	3.431	0.383	3.553	0.615
2.649	0.376	2.931	0.407	2.985	0.679
3.151	0.421	4.300	0.578	3.640	0.748
3.689	0.465	3.702	0.615	2.919	0.934
4.188	0.502	3.026	0.634	1.823	1.219
4.648	0.539	2.242	0.720	0.935	1.709
5.074	0.568	1.993	0.757	0.594	2.390
4.453	0.613	1.995	0.761	0.679	2.536
5.009	0.627	1.416	0.821	0.603	2.704
5.500	0.657	0.632	0.945		
6.107	0.679	0.204	1.052		
6.548	0.709				
5.673	0.738				
4.944	0.760				
4.092	0.834				
3.382	0.923				
2.395	1.004				
1.743	1.129				
1.244	1.262				
0.729	1.572				
0.438	1.838				
0.299	2.000				

Table A2.13. Flexure Tests Data for Trial Mixes: All Palm, at 28 Days.

0.5%Palm	
2P (kN)	**mm**
0.004	0.000
0.511	0.236
1.010	0.317
1.501	0.354
2.023	0.384
2.510	0.413
3.044	0.458
3.551	0.495
3.946	0.517
0.468	0.561
0.299	0.650
0.307	0.672
0.196	0.805
0.192	0.805
0.104	1.033

0.5%Palm-10%coarse	
2P (kN)	**mm**
0.004	0.000
0.518	0.325
1.021	0.384
0.745	0.391
1.021	0.406
1.071	0.406
1.509	0.436
2.038	0.472
2.549	0.509
3.048	0.546
3.524	0.576
3.957	0.605
0.879	0.716
0.507	0.768
0.399	0.930
0.415	0.974
0.288	1.056
0.157	1.321

0.5%Palm-20%coarse	
2P (kN)	**mm**
0.004	0.000
0.526	0.140
1.006	0.155
1.436	0.155
1.416	0.162
1.301	0.170
2.011	0.199
2.541	0.199
3.048	0.199
3.504	0.207
3.739	0.221
3.704	0.221
2.368	0.258
1.489	0.288
0.998	0.317
0.568	0.421
0.261	2.894

1%Palm	
2P (kN)	**mm**
0.031	0.000
0.203	0.236
0.238	0.768
1.129	1.225
1.501	1.255
2.073	1.277
2.514	1.299
3.117	1.321
3.904	1.351
4.422	1.366
2.414	1.469
2.007	1.572
1.597	1.786
1.098	2.207
0.998	2.340
1.002	2.340
1.017	2.377
0.695	2.908

Table A2.14. Flexure Tests Data for Trial Mixes: Banana, Steel, and Polypropylene, at 28 Days.

1%Banana	
2P (kN)	**mm**
0.031	0.000
0.507	0.192
1.017	0.258
1.524	0.295
2.019	0.310
2.526	0.347
3.025	0.354
3.520	0.413
3.650	0.428
0.699	0.760
0.772	0.819
0.633	0.871
0.649	0.893
0.503	0.989
0.495	0.989

0.5%Steel	
2P (kN)	**mm**
0.004	0.000
0.622	0.251
1.067	0.266
1.628	0.266
2.011	0.295
2.668	0.310
3.543	0.325
4.748	0.369
2.975	0.458
3.608	1.336
3.911	1.845
2.507	2.104
2.491	2.192
2.518	2.215
2.180	2.399
2.322	2.532
2.196	2.584
2.234	2.613
2.242	2.643
1.969	2.724
1.984	2.753
2.123	2.790
1.543	2.975
1.708	3.078
1.555	3.115
1.723	3.218
1.651	3.270
1.773	3.307
1.762	3.359
1.597	3.418
1.601	3.432
1.597	3.455
1.712	3.521
1.846	3.639
1.965	3.720
2.057	3.809

1%Polypropylene	
2P (kN)	**mm**
0.012	0.000
0.511	0.406
1.048	0.502
1.581	0.546
3.006	0.635
3.401	0.650
3.013	0.701
3.213	0.716
3.194	0.723
3.470	0.819
3.339	0.856
3.343	0.856
3.174	0.886
3.220	0.908
3.217	0.908
3.236	0.930
3.224	0.930
3.401	0.967
3.508	0.997
3.566	1.033
2.967	1.107
2.810	1.159
2.971	1.225
2.967	1.262
3.128	1.343
2.418	1.535
2.399	1.639
2.407	1.661
1.969	1.779
2.004	1.786
1.685	1.927
1.712	1.964
1.681	1.978

Table A2.15. Flexure Tests Data for Phase 1: Control, 0.5% Polypropylene, and 0.5% Hemp, at 7 Days.

Control		0.5% Polypropylene		0.5%Hemp	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
0.389	0.008	0.431	0.005	1.43	0.018
0.434	0.01	0.469	0.005	1.599	0.022
0.902	0.015	1.426	0.014	1.905	0.025
1.257	0.021	3.578	0.031	2.566	0.029
1.482	0.025	5.511	0.043	3.332	0.032
1.617	0.03	7.332	0.055	3.618	0.034
2.344	0.036	8.666	0.062	3.999	0.04
2.669	0.045	12.844	0.086	5.004	0.044
3.047	0.049	13.335	0.088	5.338	0.049
3.693	0.056	13.306	0.093	5.92	0.052
3.79	0.062	15.085	0.096	6.54	0.057
4.554	0.067	16.42	0.103	8.863	0.062
4.811	0.068	17.534	0.111	9.038	0.064
5.683	0.074	20.175	0.12	9.268	0.066
6.005	0.08	20.56	0.123	9.603	0.068
6.027	0.08	20.407	0.125	10.373	0.071
6.333	0.083	19.655	0.131	12.9	0.082
7.538	0.093	7.268	0.194	13.949	0.088
7.78	0.095	6.481	0.351	14.81	0.093
8.381	0.099	5.875	0.371	15.926	0.097
8.468	0.101	4.962	0.561	14.736	0.099
8.673	0.102	3.991	1.016	17.589	0.105
9.338	0.107	2.98	1.656	17.745	0.108
10.496	0.112	1.938	2.129	15.144	0.127
10.604	0.114	1.352	3.188	8.466	0.161
10.924	0.118	0.505	4.851	8.124	0.168
10.937	0.121	0.279	8.224	7.153	0.192
12.636	0.13	0.197	10.343	6.951	0.24
13.859	0.14			4.581	0.314
13.598	0.141			3.512	0.404
13.936	0.144			2.771	0.472
15.315	0.149			1.537	0.526
16.535	0.159			1.316	0.582
15.964	0.163			1.058	0.747
16.958	0.165			0.867	0.877
18.407	0.172			0.576	1.021
19.513	0.18			0.445	1.359
				0.23	4.129

Table A2.16. Flexure Tests Data for Phase 1: 0.5% Hemp, at 7 Days.

0.5%Hemp-10%coarse		0.5%Hemp-20%coarse		0.5%Hemp-30%coarse	
2P (kN)	mm	2P (kN)	mm	2P (kN)	mm
0	0	0	0	0	0
1.637	0.001	0.723	0.014	0.39	0.001
2.431	0.004	1.03	0.024	0.942	0.002
2.629	0.004	1.491	0.033	1.112	0.004
3.938	0.009	4.744	0.111	1.235	0.005
5.277	0.012	7.387	0.135	1.428	0.009
6.556	0.013	9.005	0.153	2.256	0.016
7.031	0.014	13.778	0.191	3.161	0.032
9.001	0.02	14.485	0.199	4.216	0.054
11.655	0.031	15.855	0.211	8.835	0.135
12.239	0.037	14.621	0.213	10.735	0.171
16.022	0.054	16.741	0.22	10.787	0.175
15.33	0.056	16.623	0.273	10.193	0.178
16.681	0.069	7.19	0.316	17.109	0.282
17.053	0.074	6.477	0.317	13.963	0.344
13.318	0.115	5.652	0.458	10.281	0.36
10.426	0.127	3.542	0.534	9.717	0.361
9.521	0.131	2.179	0.803	8.516	0.672
4.572	0.241	1.5	0.995	7.647	0.746
2.867	0.33	1.161	1.146	5.836	1.087
1.428	0.414	0.555	1.193	3.931	1.289
0.898	0.622	0.232	2.209	3.003	1.311
0.359	0.752	0.144	2.505	2.689	1.312
0.075	1.199			2.396	2.166
				1.16	3.438
				0.709	4.13
				0.452	9.11
				0.186	9.6

Table A2.17. Flexure Tests Data for Phase 1: 0.75% Hemp, at 7 Days.

0.75%Hemp-10%coarse		0.75%Hemp-20%coarse		0.75%Hemp-30%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
0.328	0.063	0.685	0.008	0.285	0.001
0.639	0.067	0.863	0.036	0.473	0.008
1.208	0.073	1.221	0.101	0.632	0.014
1.483	0.188	2.242	0.150	0.904	0.156
2.669	0.263	3.262	0.198	3.756	0.358
3.150	0.319	5.931	0.318	8.167	0.621
6.809	0.463	6.365	0.340	6.246	0.660
10.344	0.580	9.425	0.447	8.862	0.689
13.290	0.651	8.722	0.461	12.275	0.753
15.756	0.725	12.422	0.520	16.456	0.839
18.121	0.768	11.855	0.523	18.285	0.886
17.839	0.784	16.452	0.610	15.966	0.909
20.809	0.919	16.100	0.615	12.303	0.936
10.334	1.396	11.635	0.867	10.615	1.178
8.154	1.488	9.710	1.328	8.503	1.453
7.622	1.500	6.307	1.743	4.605	1.787
5.766	2.055	5.631	1.763	3.220	2.346
4.240	2.396	4.078	2.479	2.559	2.455
3.618	2.442	2.635	3.772	1.505	3.453
2.339	3.639	1.190	6.269	0.689	5.517
1.434	4.617	0.537	10.693	0.166	8.396
0.701	5.530	0.142	13.390		
0.181	7.215				

Table A2.18. Flexure Tests Data for Phase 1: 1% Hemp, at 7 Days.

1%Hemp-10%coarse		1%Hemp-20%coarse		1%Hemp-30%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
3.037	0.114	0.373	0.002	1.372	0.036
3.092	0.127	0.540	0.002	1.691	0.041
6.303	0.237	1.054	0.087	2.759	0.057
8.449	0.296	2.627	0.227	6.273	0.103
11.275	0.359	4.417	0.298	8.842	0.127
13.740	0.424	5.010	0.323	12.299	0.160
13.495	0.429	9.132	0.412	11.759	0.161
13.519	0.435	11.137	0.474	18.350	0.263
16.368	0.599	12.752	0.500	21.722	0.365
14.252	0.652	15.091	0.545	18.635	0.471
11.864	1.162	14.154	0.548	9.903	0.686
12.162	1.335	17.587	0.686	6.367	1.056
8.760	1.931	16.517	0.867	4.388	1.302
7.601	2.339	13.794	0.991	2.737	1.981
3.775	3.400	7.494	1.717	0.949	4.163
2.327	4.529	5.768	1.954	0.152	6.305
1.091	5.124	3.679	2.819		
0.940	6.161	2.413	3.414		
0.137	7.443	1.810	4.323		
		1.265	4.549		
		0.813	6.094		
		0.515	7.985		
		0.356	8.451		
		0.143	12.208		

Table A2.19. Flexure Tests Data for Phase 1: Control, 0.5% Polypropylene, and 0.5% Hemp, at 28 Days.

Control		0.5%Polypropylene		0.5%Hemp	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
0.560	0	0.637	0.001	1.850	0.104
0.697	0.002	2.687	0.002	3.596	0.209
1.195	0.002	7.228	0.004	5.618	0.296
1.674	0.003	12.353	0.011	6.646	0.337
2.058	0.004	16.069	0.013	7.364	0.359
2.713	0.004	20.581	0.014	11.410	0.457
3.860	0.005	19.799	0.014	12.025	0.485
5.083	0.005	6.965	0.014	15.442	0.552
6.618	0.007	6.547	0.014	15.198	0.565
7.191	0.009	6.269	0.015	16.081	0.584
7.985	0.010	6.047	0.016	12.834	0.761
8.828	0.010	6.893	0.037	5.310	0.809
10.165	0.010	5.727	0.385	5.309	0.821
10.709	0.012	2.601	0.810	3.829	1.352
11.286	0.015	2.039	0.828	2.119	1.928
13.263	0.016	2.128	0.845	1.855	1.950
13.405	0.021	2.562	0.859	1.796	1.957
14.660	0.021	2.632	0.930	1.704	1.962
15.786	0.023	2.309	0.967	1.630	1.964
17.378	0.025	1.695	1.723	1.649	1.965
19.645	0.027	0.433	2.664	1.508	1.966
19.611	0.029	0.562	2.834	1.573	1.967
19.956	0.030	0.635	2.842	1.573	1.968
21.912	0.031	0.283	2.889	1.565	1.969
23.158	0.032	0.215	3.680	1.362	1.969
25.947	0.033			1.340	1.969
				1.449	1.970
				1.607	1.974
				1.599	1.976
				2.017	2.041
				1.265	2.918
				0.322	3.209
				0.455	3.220
				0.256	3.226
				0.772	3.348
				0.340	4.176

Table A2.20. Flexure Tests Data for Phase 1: 0.5% Hemp, at 28 Days.

0.5%Hemp-10%coarse		0.5%Hemp-20%coarse		0.5%Hemp-30%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
0.258	0.002	0.530	0.002	1.158	0.032
0.354	0.003	1.243	0.051	2.865	0.130
0.449	0.042	2.423	0.118	8.717	0.298
0.576	0.068	2.752	0.121	9.787	0.319
1.178	0.088	3.100	0.125	13.097	0.376
2.712	0.135	3.640	0.135	13.152	0.391
3.216	0.159	3.783	0.142	12.681	0.394
4.270	0.194	5.691	0.187	13.179	0.398
5.852	0.251	5.724	0.190	14.816	0.421
5.714	0.252	6.548	0.209	15.744	0.444
6.197	0.267	9.883	0.272	17.300	0.469
9.778	0.323	10.488	0.295	18.155	0.486
11.820	0.359	13.511	0.350	21.470	0.535
14.689	0.397	12.733	0.352	22.276	0.562
16.025	0.423	16.903	0.399	21.957	0.562
17.606	0.445	20.681	0.466	19.209	0.707
16.755	0.445	20.074	0.467	6.017	0.986
21.302	0.489	19.645	0.469	3.740	1.509
22.137	0.507	20.331	0.475	2.232	1.835
21.542	0.507	16.087	0.732	1.322	2.510
21.712	0.509	4.167	0.946	0.812	3.152
13.490	0.748	1.756	2.406	0.534	3.345
6.046	0.854	0.582	3.480	0.335	3.375
5.492	0.856	0.998	10.436	0.298	4.852
5.549	0.857	1.117	10.439	0.035	5.971
5.532	0.965				
3.477	1.094				
3.138	1.098				
3.580	1.209				
2.460	1.347				
2.601	1.416				
1.315	1.822				
1.376	1.824				
1.464	1.834				
1.561	2.162				
0.891	3.629				
0.607	3.996				
0.468	4.003				
0.687	5.116				
1.082	10.129				

Table A2.21. Flexure Tests Data for Phase 1: 0.75% Hemp, at 28 Days.

0.75%Hemp-10%coarse		0.75%Hemp-20%coarse		0.75%Hemp-30%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
1.295	0.069	1.249	0.002	0.425	0.005
4.245	0.208	2.753	0.002	4.994	0.084
6.353	0.282	4.384	0.003	5.611	0.093
6.393	0.284	6.822	0.019	6.433	0.098
8.003	0.318	8.389	0.034	8.619	0.115
10.647	0.386	10.074	0.050	8.758	0.116
11.414	0.398	13.109	0.070	9.485	0.120
13.932	0.448	12.510	0.075	9.963	0.120
13.694	0.449	22.745	0.127	10.782	0.129
14.783	0.468	16.384	0.168	10.806	0.131
15.347	0.485	13.608	0.177	10.425	0.131
19.924	0.554	7.148	0.663	15.373	0.158
20.913	0.587	5.965	0.681	15.430	0.162
21.608	0.602	3.165	0.721	20.858	0.191
25.078	0.664	2.270	1.005	18.624	0.242
11.485	1.002	0.985	1.638	9.797	0.296
8.036	1.419	0.489	2.457	7.761	0.501
5.943	1.717	0.199	3.060	1.214	1.681
2.649	3.098	0.097	4.402	0.338	2.430
0.780	4.791				
0.248	6.063				

Table A2.22. Flexure Tests Data for Phase 1: 1% Hemp, at 28 Days.

1%Hemp-10%coarse		1%Hemp-20%coarse		1%Hemp-30%coarse	
2P (kN)	**mm**	**2P (kN)**	**mm**	**2P (kN)**	**mm**
0	0	0	0	0	0
0.222	0.004	0.279	0.006	1.066	0.106
0.371	0.033	0.745	0.009	2.426	0.215
0.508	0.126	1.208	0.121	3.165	0.259
2.661	0.148	1.929	0.235	4.087	0.299
3.058	0.189	1.873	0.239	4.870	0.335
3.555	0.228	2.945	0.327	5.505	0.365
4.674	0.279	4.973	0.402	7.881	0.430
10.674	0.419	5.660	0.425	8.773	0.457
12.636	0.477	6.349	0.438	8.881	0.460
13.249	0.493	8.932	0.496	8.983	0.467
17.127	0.719	10.796	0.546	11.937	0.520
12.841	0.786	11.535	0.556	11.243	0.527
11.440	0.943	18.849	0.694	12.244	0.542
7.899	1.315	20.705	0.758	16.411	0.615
3.427	1.946	15.591	0.993	17.496	0.639
2.820	2.284	11.514	1.243	20.374	0.694
1.524	3.080	8.507	1.633	21.757	0.714
0.579	4.292	5.401	2.101	24.099	0.837
0.622	5.073	3.475	2.622	12.225	1.646
0.377	6.599	1.960	3.433	5.295	2.060
		0.866	5.532	4.473	2.508
		0.403	8.247	2.118	3.620
				0.324	6.124

Table A2.23. Flexure Tests Data for Phase 2: Control, at 28 Days.

F1-Control						F2-Control					
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	141.0	18.8	59.6	27.0	0.0	0.0	130.3	13.5	97.8	18.2
0.8	0.0	140.5	18.9	59.5	27.0	0.6	0.3	130.0	13.5	96.6	18.4
1.1	0.0	139.1	18.9	59.8	27.0	1.2	0.3	130.5	13.5	95.9	18.5
1.9	0.0	138.5	19.0	59.9	27.0	5.2	0.7	129.2	13.6	94.7	18.8
5.7	0.3	137.5	19.6	60.3	27.0	5.8	0.7	129.6	13.6	93.8	18.9
10.4	0.4	136.1	20.0	60.1	27.0	10.9	1.0	131.1	13.7	92.7	19.0
15.6	0.5	135.0	20.2	58.5	27.0	15.1	1.2	131.3	13.7	91.1	19.3
20.4	0.7	133.5	20.3	59.4	27.0	20.8	1.4	130.1	13.7	90.3	19.4
26.1	1.0	132.4	20.7	59.6	27.0	26.1	1.7	131.0	14.5	89.9	19.5
30.1	1.3	130.4	20.8	59.1	27.0	29.8	2.0	128.8	14.7	88.9	19.6
35.5	1.6	129.8	20.9	60.1	27.1	36.0	2.4	126.9	14.8	87.6	19.7
41.0	2.0	128.0	21.3	59.0	27.1	40.1	2.7	125.3	14.9	86.1	19.8
45.1	2.2	127.7	21.5	59.2	27.1	45.4	3.0	123.9	15.0	85.1	19.8
51.9	2.7	126.6	21.8	59.0	27.1	50.7	3.4	124.3	15.1	84.3	19.9
56.0	3.0	125.0	21.8	59.2	27.1	56.1	3.8	123.7	15.3	83.3	20.1
60.0	3.3	122.1	22.5	59.2	27.1	60.5	4.3	121.5	15.3	82.2	20.2
65.0	3.7	119.0	22.6	59.0	27.1	65.9	4.7	121.3	15.3	81.4	20.3
70.1	4.1	115.5	22.7	59.0	27.1	70.2	5.0	120.5	15.3	80.8	20.3
75.4	4.6	112.1	22.8	58.3	27.1	76.3	5.5	119.3	15.4	79.6	20.3
80.0	5.0	110.3	22.8	58.0	27.2	80.8	6.0	118.3	15.4	78.3	20.4
85.9	5.5	106.7	22.9	58.4	27.2	85.4	6.4	119.0	15.4	77.2	20.5
90.2	5.9	103.8	22.9	58.5	27.2	90.7	6.9	117.1	15.4	76.1	20.5
95.5	6.5	102.1	23.1	58.9	27.2	95.1	7.5	117.7	15.4	75.8	20.5
100.2	7.0	100.5	23.2	58.2	27.2	100.4	8.0	118.1	15.6	76.1	20.5
105.2	7.5	95.7	23.5	58.7	27.2	104.2	8.5	116.2	15.6	75.5	20.5
110.8	8.2	90.6	23.9	59.2	27.2	106.1	8.6	115.0	15.6	74.5	20.5
115.7	8.8	84.3	24.8	59.0	27.2	108.6	9.3	116.4	15.6	75.1	20.5
120.8	9.6	79.8	25.4	60.1	27.2	111.3	9.4	117.7	15.7	74.3	20.5
125.2	10.3	76.8	26.6	60.3	27.2	116.7	9.8	116.7	15.7	73.5	20.5
126.7	10.4	66.7	26.7	59.9	27.3	120.5	10.4	114.8	15.7	72.5	20.6
130.0	11.3	60.6	26.9	59.7	27.3	125.0	11.4	114.5	15.7	71.9	20.6
135.1	12.8	59.8	26.9	58.9	27.3	125.5	11.4	116.5	15.8	72.0	20.6
135.4	12.9	60.2	26.9	59.6	27.3	129.4	12.8	114.7	15.9	72.1	20.6
135.3	13.1	59.8	26.9	59.1	27.3	130.2	12.9	113.7	15.9	72.2	20.6
140.7	15.6	58.9	26.9	58.5	27.3	130.2	12.9	112.3	16.2	71.8	20.6
141.1	17.4	58.8	26.9	58.1	27.3	130.0	13.0	109.2	16.5	72.1	20.6
142.0	17.8	58.7	26.9	58.0	27.3	129.8	13.1	107.9	16.6		
141.6	17.9	58.6	26.9	57.8	27.3	129.5	13.1	107.0	16.8		
141.0	18.0	58.3	26.9	58.1	27.3	128.7	13.1	105.2	16.9		
141.2	18.1	59.5	26.9	58.0	27.3	129.4	13.1	103.0	17.0		
140.9	18.2	58.9	26.9			130.7	13.2	102.2	17.0		
140.2	18.3	58.8	26.9			129.9	13.3	101.5	17.5		
140.9	18.4	59.0	27.0			131.4	13.4	100.1	17.6		
140.6	18.4	59.2	27.0			130.2	13.4	99.1	17.9		
141.7	18.6	59.8	27.0			129.1	13.4	98.9	18.0		

Table A2.24. Shear Tests Data for Phase 2: Control, at 28 Days.

S1-Control						S2-Control							
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	49.7	2.9	57.2	9.1	0.0	0.0	60.3	4.0	63.3	10.4	43.5	15.1
0.3	0.0	50.9	2.9	55.5	9.2	0.2	0.0	61.7	4.1	64.4	10.4	43.2	15.3
0.7	0.0	52.0	3.0	54.3	9.2	0.8	0.0	62.9	4.4	63.9	10.5	42.6	15.3
0.9	0.0	52.6	3.2	54.0	9.2	2.4	0.1	64.5	4.5	63.8	10.5	42.4	15.4
0.9	0.0	54.9	3.3	53.2	9.3	4.1	0.2	65.6	4.7	64.9	10.6	42.0	15.5
1.7	0.0	55.6	3.4	52.0	9.4	5.4	0.3	67.0	4.8	64.6	10.6	41.4	15.5
2.0	0.0	56.4	3.5	50.9	9.6	7.9	0.4	68.3	5.0	60.4	10.8	40.3	15.5
3.4	0.1	57.6	3.7	49.5	9.7	8.0	0.4	69.8	5.2	56.2	10.8	39.7	15.5
4.6	0.1	58.6	3.8	47.3	9.7	9.8	0.4	70.4	5.2	55.5	10.8	38.5	15.5
5.2	0.2	59.4	3.9	46.1	10.6	11.5	0.5	71.0	5.3	54.9	11.0	38.3	15.5
6.1	0.2	61.0	4.0	45.9	10.7	13.1	0.6	72.5	5.6	52.5	11.0	38.0	15.5
7.4	0.2	61.1	4.1	44.8	11.4	15.2	0.6	74.2	5.7	53.4	11.0	37.5	15.5
8.4	0.3	62.4	4.3	43.9	11.9	16.6	0.7	75.9	5.9	53.3	11.1	37.8	15.5
9.6	0.3	63.6	4.4	43.0	11.9	19.4	0.8	76.2	6.2	52.7	11.2	38.1	15.5
10.6	0.3	65.2	4.5	43.1	12.2	21.5	0.9	77.6	6.3	51.6	11.3	37.7	15.5
11.4	0.4	66.4	4.7	43.4	12.3	22.6	1.1	78.1	6.4	52.1	11.3	37.2	15.5
12.7	0.4	67.8	5.0	44.1	12.4	23.4	1.1	79.0	6.4	52.2	11.4	37.9	15.5
14.5	0.5	68.7	5.1	44.0	12.6	24.5	1.1	80.5	6.5	51.8	11.5		
16.0	0.5	69.3	5.1	44.0	12.6	25.3	1.2	81.1	6.9	51.1	11.6		
16.5	0.5	70.4	5.2	43.8	12.7	26.4	1.3	82.0	7.0	51.4	11.7		
17.3	0.6	71.9	5.7	44.1	12.8	27.1	1.4	83.3	7.1	50.8	11.8		
19.4	0.7	72.6	5.8	43.8	12.9	29.5	1.4	83.7	7.1	50.2	11.8		
20.6	0.7	74.0	5.9	43.7	13.3	30.7	1.5	85.2	7.2	50.9	11.8		
21.9	0.8	74.4	5.9	42.8	13.4	31.1	1.6	86.2	7.3	51.2	12.0		
22.7	0.9	75.8	6.1	41.4	13.5	32.2	1.7	87.3	7.9	50.9	12.2		
24.7	1.0	77.2	6.2	40.9	13.5	33.3	1.8	88.8	8.0	50.2	12.3		
27.7	1.2	79.0	6.4	40.3	13.9	34.8	1.8	90.0	8.2	50.2	12.4		
29.5	1.3	80.1	6.9	40.0	14.1	36.5	1.9	90.9	8.3	50.0	12.5		
30.1	1.4	81.0	7.0	39.4	14.2	37.6	2.1	91.3	8.4	47.8	12.6		
29.6	1.4	83.5	7.9	39.4	14.6	38.8	2.2	90.0	8.4	49.1	12.6		
31.4	1.4	82.8	8.1	39.0	14.7	40.9	2.2	95.2	9.6	49.1	12.7		
33.0	1.6	80.6	8.2	38.7	14.9	42.1	2.3	94.0	9.7	48.9	12.8		
34.1	1.6	79.2	8.2	38.4	15.1	43.9	2.5	94.8	9.9	47.3	12.9		
35.7	1.7	77.5	8.3	37.8	15.2	45.9	2.6	83.3	10.0	47.2	13.3		
36.5	1.8	77.1	8.4	37.0	15.4	47.3	2.7	74.8	10.1	47.0	13.4		
37.1	1.9	75.5	8.4	35.2	15.4	48.9	2.9	72.3	10.2	45.5	13.5		
38.7	2.0	75.0	8.5	34.9	15.4	50.0	3.0	67.7	10.2	46.1	13.6		
39.4	2.0	73.4	8.6	32.7	15.4	50.3	3.1	67.2	10.2	45.8	13.7		
40.1	2.1	72.8	8.6	33.9	15.4	51.2	3.2	66.4	10.2	45.2	13.9		
41.8	2.2	71.4	8.7	35.6	15.5	52.4	3.2	65.0	10.2	44.6	14.0		
43.4	2.3	71.1	8.8	34.7	15.5	55.0	3.4	65.3	10.2	44.7	14.2		
45.3	2.4	69.1	8.8	35.0	15.5	55.8	3.5	64.5	10.2	44.6	14.4		
46.9	2.5	66.3	8.9	35.1	15.5	56.7	3.6	65.4	10.3	44.2	14.5		
47.6	2.6	63.1	9.0			57.4	3.8	65.5	10.4	43.9	14.7		
48.7	2.8	60.9	9.1			58.8	3.9	64.1	10.4	43.8	14.9		

Table A2.25. Bond Tests Data for Phase 2: Control, at 28 Days.

B1-Control					B2-Control			
P (kN)	mm	P (kN)	mm		P (kN)	mm	P (kN)	mm
0.0	0.0	47.7	2.9		0.0	0.0	55.9	3.0
0.5	0.0	49.0	3.0		0.6	0.0	56.6	3.1
0.9	0.0	50.6	3.1		1.5	0.1	58.0	3.2
1.4	0.1	51.9	3.2		1.6	0.1	58.8	3.3
2.8	0.3	52.6	3.4		2.4	0.2	60.7	3.4
3.8	0.4	53.8	3.5		3.5	0.3	61.7	3.6
4.9	0.5	54.6	3.5		4.7	0.4	62.2	3.7
5.1	0.5	55.4	3.6		5.9	0.4	63.0	3.7
6.3	0.5	56.3	3.7		7.0	0.5	64.4	3.8
8.3	0.6	57.7	3.8		8.1	0.5	65.2	3.9
9.9	0.6	59.4	3.9		9.9	0.6	64.5	3.9
11.7	0.7	61.3	4.0		10.2	0.6	64.2	3.9
12.4	0.7	62.9	4.3		13.1	0.6	63.3	3.9
14.0	0.8	63.6	4.4		14.2	0.7	63.4	4.0
15.0	0.8	64.0	4.5		16.2	0.8	62.1	4.0
15.5	0.8	42.9	5.4		17.1	0.8	61.7	4.0
16.5	0.9	24.1	6.7		19.0	0.9	61.0	4.0
17.8	1.0	23.3	7.0		19.2	0.9	60.8	4.0
19.0	1.0	22.1	7.2		20.4	0.9	61.7	4.0
20.1	1.0	21.5	7.3		21.5	1.0	60.2	4.0
21.7	1.1	20.9	7.5		22.1	1.0	61.6	4.0
22.9	1.2	20.0	7.7		23.4	1.0	62.0	4.0
23.9	1.2	18.9	8.0		25.9	1.2	61.8	4.0
24.4	1.3	17.6	8.3		26.1	1.3	62.0	4.0
25.0	1.3	17.0	8.5		28.1	1.3	61.2	4.0
26.9	1.5	15.8	8.9		29.2	1.4	60.7	4.0
27.3	1.5	15.2	9.1		31.0	1.5	58.0	4.5
28.7	1.5	14.6	9.3		31.5	1.5	59.2	4.5
29.8	1.6	13.5	9.8		33.4	1.6	59.6	4.7
30.9	1.7	12.9	10.0		34.7	1.7	58.3	4.7
31.4	1.8	11.4	10.6		35.8	1.7	57.7	4.8
33.2	1.8	11.0	10.6		36.6	1.8	59.5	4.8
34.8	1.9	10.3	10.6		37.1	1.9	58.9	4.8
36.0	2.0	10.1	10.7		38.3	1.9	24.2	6.0
36.1	2.0	10.0	10.7		39.3	2.0	12.7	6.5
37.5	2.2	9.9	10.7		42.0	2.1	13.4	6.7
38.9	2.2	10.0	10.7		43.9	2.3	12.3	7.3
40.8	2.5	10.1	10.7		45.1	2.3	13.5	7.4
42.1	2.5	10.0	10.7		47.0	2.4	12.7	7.4
43.6	2.6	10.1	10.7		47.5	2.5	13.5	7.4
44.8	2.7	10.1	10.7		48.3	2.6	12.6	7.4
45.9	2.7	10.4	10.7		49.5	2.6	12.8	7.4
47.0	2.8	5.7	10.8		51.2	2.7	13.8	7.4
					52.9	2.9		
					54.8	3.0		

Table A2.26. Flexure Tests Data for Phase 2: 0.75% Hemp, at 28 Days.

F1-0.75%HP-20%coarse						F2-0.75%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	120.2	16.1	84.4	34.9	0.0	0.0	116.0	22.4	84.5	36.6
0.6	0.0	119.7	16.3	83.6	35.8	1.0	0.0	117.5	22.6	82.8	36.7
1.0	0.0	118.5	19.5	81.7	36.2	1.8	0.1	116.5	22.7	81.9	36.8
1.4	0.0	118.1	19.6	80.3	36.3	2.3	0.1	117.9	22.9	80.7	37.0
2.3	0.0	117.6	19.8	79.7	36.3	3.2	0.1	119.4	23.3	79.0	37.2
2.6	0.0	117.3	20.1	72.7	39.4	4.7	0.1	118.1	23.9	77.3	37.4
4.1	0.1	117.0	20.2	69.6	40.6	5.9	0.1	117.6	24.0	76.0	37.5
5.5	0.1	116.2	20.5	67.7	44.2	6.8	0.2	118.1	24.4	75.1	37.7
7.2	0.2	116.3	20.7	65.7	48.8	7.6	0.2	115.8	24.4	74.2	37.8
7.5	0.2	115.8	20.9	64.8	50.1	8.7	0.2	116.7	24.7	72.5	38.0
8.1	0.2	114.3	21.1	62.0	50.3	9.7	0.3	116.2	24.7	70.9	38.1
8.6	0.2	114.0	21.1	60.1	50.3	10.9	0.3	117.0	24.9	69.1	38.4
9.6	0.3	114.8	21.7	60.3	50.7	15.0	0.5	116.3	25.3	67.2	38.6
10.3	0.3	113.0	21.8	59.3	51.3	20.4	0.8	116.5	25.5	65.4	38.7
11.5	0.3	114.4	22.0			25.2	1.1	115.9	25.8	63.8	38.8
15.2	0.5	114.1	22.2			30.3	1.4	116.8	26.1	61.8	39.0
16.6	0.5	113.2	22.5			35.4	1.7	115.6	27.1	58.2	40.2
20.7	0.7	112.0	22.6			40.2	2.0	114.4	27.3	58.2	40.2
25.1	0.9	112.7	22.8			45.5	2.4	113.7	28.1	56.3	40.3
31.4	1.3	112.1	22.9			51.9	3.0	112.3	29.0		
35.8	1.6	111.6	23.2			56.4	3.3	110.2	29.3		
41.7	2.0	110.5	23.2			60.2	3.6	108.9	29.4		
45.0	2.2	111.1	23.3			65.4	4.0	110.3	29.7		
51.9	3.0	110.8	23.4			71.3	4.4	109.4	29.9		
55.9	3.1	109.2	23.6			75.1	4.8	109.0	30.2		
62.8	3.5	108.4	24.1			80.0	5.2	107.8	30.4		
65.5	3.8	105.6	24.1			85.4	5.8	107.0	30.7		
69.8	4.3	106.3	24.1			90.4	6.3	105.9	31.2		
73.8	4.6	104.9	24.1			96.2	6.9	105.0	31.7		
80.1	5.4	103.6	24.1			100.6	7.7	103.2	32.5		
85.6	5.9	105.4	24.2			104.9	8.4	102.4	32.5		
90.4	6.9	106.0	24.9			107.0	8.7	101.7	32.6		
98.9	7.3	106.8	25.0			110.2	9.7	100.8	34.0		
102.9	8.5	107.1	25.5			116.0	16.6	99.8	34.2		
106.7	9.6	106.8	25.9			112.9	17.3	97.8	34.3		
108.8	10.5	105.9	26.1			116.1	17.6	96.7	34.4		
110.1	11.1	103.5	27.7			116.9	17.8	97.1	34.9		
111.3	11.2	102.5	28.1			117.3	18.1	95.6	35.1		
112.8	12.1	101.1	28.7			118.1	18.3	93.9	35.3		
113.1	12.2	100.2	28.8			118.0	18.7	92.0	35.6		
114.2	12.4	97.5	29.8			118.0	18.8	90.3	35.8		
115.8	12.7	93.4	30.3			116.7	18.9	89.1	35.9		
117.0	13.7	92.7	34.5			118.9	20.1	88.0	36.1		
118.2	13.9	90.1	34.6			119.9	22.2	87.3	36.3		
119.7	15.4	89.8	34.8			118.4	22.3	85.9	36.4		

Table A2.27. Shear Tests Data for Phase 2: 0.75% Hemp, at 28 Days.

S1-0.75%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	83.8	13.5	40.8	30.0
0.8	0.0	84.1	13.6	39.6	30.4
1.4	0.1	84.0	13.6	38.3	30.8
2.3	0.3	84.1	13.7	37.4	31.1
4.7	0.7	83.8	13.9	36.8	31.4
5.7	0.8	83.5	14.2	36.1	31.8
6.6	0.8	82.8	14.4	34.9	32.2
7.5	0.8	81.5	14.5	34.0	32.5
8.5	0.9	81.2	14.9	33.2	32.9
9.9	0.9	80.2	15.1	32.3	33.2
11.4	1.0	79.6	15.2	31.8	33.5
15.7	1.2	78.5	15.9	31.2	33.8
20.3	1.5	77.8	16.4	30.4	34.1
25.6	1.8	76.9	16.7	30.1	34.3
30.9	2.1	75.4	17.4	29.8	34.8
35.9	2.5	74.4	17.8	29.0	35.3
40.4	2.8	73.6	18.1	28.3	35.8
45.8	3.2	72.8	18.4	27.9	36.2
50.8	3.6	71.2	19.1	27.3	36.4
55.2	3.9	69.7	19.8	27.0	36.6
60.5	4.3	69.4	20.5	26.6	36.6
61.6	4.6	69.3	20.9	26.7	36.7
63.6	4.7	68.7	21.9	26.5	36.8
64.2	4.7	68.5	22.2	25.1	36.8
65.6	4.8	67.9	22.7	24.9	36.9
66.4	5.1	67.5	22.9	23.7	36.9
67.9	5.1	66.9	23.1		
69.8	5.3	67.1	23.3		
71.6	5.3	67.2	23.5		
73.2	6.3	66.9	23.8		
76.0	6.4	66.6	24.1		
79.9	6.7	64.6	24.9		
82.2	6.9	64.4	25.7		
83.9	7.2	63.1	26.1		
84.5	7.4	62.1	26.3		
85.5	10.3	61.4	26.7		
85.1	10.4	59.6	27.0		
85.7	10.5	58.3	27.3		
85.1	10.7	54.1	27.7		
86.7	11.1	49.5	28.1		
88.3	11.4	47.7	28.4		
86.1	11.6	45.8	28.7		
84.8	11.7	44.2	29.0		
84.8	12.7	42.8	29.3		
84.3	13.2	41.9	29.6		

S2-0.75%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	82.0	16.2	28.8	27.3
0.5	0.0	81.6	16.3	27.9	27.3
1.9	0.1	80.8	16.4	27.5	27.4
2.3	0.1	81.8	16.7		
3.7	0.1	81.5	16.9		
4.6	0.1	81.2	17.2		
5.7	0.2	80.9	17.4		
6.4	0.2	80.5	17.9		
7.6	0.3	79.8	18.1		
9.2	0.3	79.0	18.7		
10.4	0.4	78.1	18.9		
15.4	0.6	76.7	19.0		
20.8	0.9	75.4	19.0		
25.0	1.2	76.3	19.2		
30.9	1.6	76.0	19.3		
35.9	2.0	75.3	19.5		
40.8	2.3	74.5	19.6		
45.3	2.7	72.6	19.7		
50.9	3.1	73.9	19.9		
57.0	3.5	70.1	20.3		
62.8	4.0	64.2	20.7		
66.9	4.5	58.8	21.3		
70.2	4.7	57.3	21.8		
71.6	4.8	56.9	22.6		
73.0	5.1	57.1	23.8		
75.7	5.2	56.8	24.1		
77.7	5.4	55.7	24.4		
79.6	5.7	54.3	24.7		
82.3	6.0	51.9	24.8		
82.6	6.3	49.7	25.0		
83.3	6.4	45.0	25.1		
83.1	6.5	37.1	25.3		
83.4	9.6	34.1	25.5		
83.7	9.7	33.1	25.7		
83.8	10.1	32.5	25.9		
84.1	13.7	31.8	26.1		
83.8	13.9	32.3	26.2		
82.8	14.0	32.3	26.5		
83.3	14.4	31.7	26.9		
83.3	14.6	31.2	27.0		
83.6	14.9	30.7	27.1		
83.5	15.1	30.3	27.2		
83.7	15.3	29.9	27.3		
82.9	15.7	29.6	27.3		
82.8	15.9	29.2	27.3		

Table A2.28. Bond Tests Data for Phase 2: 0.75% Hemp, at 28 Days.

B1-0.75%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	28.2	7.5	10.1	15.9
0.6	0.0	27.8	7.5	9.9	16.1
0.9	0.0	27.8	7.6	9.8	16.2
1.7	0.1	28.4	7.6	9.7	16.4
2.8	0.2	28.3	7.8	9.5	16.7
3.9	0.3	27.5	8.0	8.9	17.0
4.4	0.3	26.6	8.2	8.6	17.0
5.1	0.4	25.7	8.4	8.5	17.0
10.4	0.7	24.4	8.7	8.4	17.0
16.7	1.0	23.5	8.8	8.1	17.0
20.7	1.4	22.3	8.9	7.6	17.0
25.6	1.6	22.3	9.0	8.1	17.1
31.0	2.0	22.0	9.1	8.0	17.1
36.6	2.4	21.9	9.2	7.9	17.1
40.5	2.7	21.5	9.4	8.0	17.1
45.4	3.1	20.9	9.5	8.2	17.1
50.0	3.4	20.5	9.6	8.1	17.1
55.3	3.8	20.0	9.7	7.8	17.1
60.8	4.4	19.5	9.9	7.6	17.1
61.9	4.5	18.6	10.0	7.5	17.1
62.2	4.5	18.1	10.0	7.3	19.5
63.6	5.0	17.9	10.2	7.2	19.7
63.8	5.1	17.6	10.3	7.0	19.9
63.1	5.2	17.0	10.5	7.0	20.1
62.0	5.3	16.3	10.8	6.9	20.4
59.4	5.4	15.7	11.0	6.8	20.6
53.3	5.6	15.0	11.3	6.7	20.7
46.9	5.7	14.6	11.3	6.7	20.9
44.5	5.8	14.5	11.5	6.6	21.1
41.8	5.9	14.0	11.7	6.6	21.3
40.4	5.9	13.8	11.9	6.5	21.7
38.9	5.9	13.6	12.0	5.6	24.1
39.5	6.0	13.3	12.3	5.4	24.3
36.7	6.0	12.9	12.6	5.5	24.5
35.5	6.0	12.4	12.9	4.3	31.0
36.4	6.0	12.3	13.1	4.2	31.0
36.0	6.1	12.1	13.4	3.6	31.0
34.7	6.1	11.8	13.7	3.5	31.0
35.1	6.1	11.5	13.9	3.5	31.0
34.6	6.1	11.4	14.2	3.6	31.0
30.4	7.3	11.2	14.5	3.5	31.1
29.7	7.4	10.9	14.9		
28.9	7.4	10.7	15.1		
27.2	7.5	10.6	15.3		
27.7	7.5	10.3	15.7		

B2-0.75%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	55.0	3.7	17.1	12.5
0.5	0.0	53.9	3.7	16.3	12.9
1.0	0.0	54.3	3.7	15.7	13.2
1.6	0.2	55.1	3.8	15.2	13.5
2.6	0.4	57.7	3.9	15.0	13.9
3.6	0.5	59.6	4.1	14.5	14.2
4.2	0.6	62.3	4.1	14.0	14.5
5.2	0.6	63.1	4.2	13.9	14.8
6.5	0.6	59.6	4.2	13.6	15.2
7.8	0.7	56.7	4.2	13.4	15.5
8.8	0.7	55.2	4.3	13.2	15.8
9.4	0.7	50.7	4.3	13.0	16.0
10.6	0.8	54.0	4.3	12.9	16.4
12.0	0.8	52.7	4.3	12.6	16.9
12.3	0.9	58.8	4.4	12.5	17.3
13.5	0.9	60.1	4.4	12.2	17.8
14.3	1.0	63.6	4.5	12.2	18.1
15.7	1.0	64.0	4.6	11.7	18.5
16.6	1.1	64.6	4.6	11.9	18.8
17.4	1.1	64.3	4.6	11.7	19.4
19.0	1.2	64.8	4.7	11.4	19.9
21.0	1.2	66.1	4.8	10.8	22.9
21.8	1.3	66.1	4.9	10.7	23.5
22.2	1.3	62.7	5.1	10.2	23.6
23.4	1.4	51.4	5.6	10.5	24.9
24.6	1.5	43.3	5.9	9.9	28.5
25.4	1.5	38.9	6.0		
27.0	1.6	37.6	6.0		
27.7	1.7	38.7	6.1		
29.9	1.8	39.7	6.1		
31.4	1.8	36.6	6.1		
32.5	1.9	35.8	7.2		
34.5	2.0	33.4	7.6		
36.5	2.2	30.5	8.1		
38.3	2.3	28.0	8.5		
39.9	2.4	26.1	8.9		
41.7	2.5	24.9	9.3		
42.9	2.6	23.6	9.6		
43.8	2.7	20.6	10.6		
45.0	2.7	20.4	10.9		
46.5	2.8	19.4	11.3		
47.9	3.0	18.7	11.6		
50.2	3.1	18.2	11.7		
52.0	3.2	18.1	11.8		
54.5	3.7	17.8	12.0		

Table A2.29. Flexure Tests Data for Phase 2: 1% Hemp, at 28 Days.

F1-1%HP-20%coarse						F2-1%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	132.3	19.1	103.0	36.7	0.0	0.0	141.2	16.1	121.0	22.5
0.5	0.0	130.0	19.4	100.7	39.9	0.5	0.0	139.7	16.2	120.5	22.5
1.6	0.1	128.0	19.7	98.3	39.9	1.0	0.1	137.5	16.9	120.3	22.6
2.7	0.2	124.0	20.1	98.4	40.2	2.9	0.1	138.5	17.0	119.5	22.6
3.2	0.4	118.7	20.2	97.3	41.1	4.8	0.2	139.8	17.1	117.5	22.6
8.8	1.0	116.3	20.2	96.4	41.3	7.2	0.4	140.4	17.3	112.0	22.6
10.3	1.1	115.1	20.2	95.7	41.5	9.6	0.5	142.0	17.6	114.9	22.6
16.0	1.5	115.2	20.5	94.9	41.6	10.9	0.6	143.0	17.8	118.0	22.6
21.1	1.7	113.5	20.5	93.9	41.9	15.4	0.8	143.5	18.1	116.9	22.6
27.9	2.1	111.7	20.6	89.2	41.9	21.1	1.1	144.4	18.7	117.3	22.7
32.7	2.4	111.2	20.6	86.8	42.0	26.8	1.5	144.5	19.0	117.8	22.7
36.7	2.7	111.9	20.8	87.2	42.0	32.1	1.9	143.7	19.3	118.4	22.8
37.2	2.8	109.2	21.1			37.5	2.2	142.4	19.9	118.1	22.9
42.5	3.0	108.4	21.2			42.1	2.5	139.5	19.9	116.8	22.9
48.8	3.4	106.4	21.3			48.4	3.0	139.1	20.3	116.3	22.9
53.9	4.0	105.2	21.4			53.3	3.3	137.8	20.3	115.7	23.0
59.1	4.2	100.3	22.4			58.9	4.0	137.5	20.5	114.4	23.0
65.6	4.6	99.8	22.8			64.3	4.2	136.4	20.6	111.8	23.0
70.0	5.2	98.8	23.1			71.4	4.7	137.1	20.7	115.4	23.1
75.8	5.4	97.8	23.4			78.0	5.4	136.5	20.7	111.8	23.1
81.5	5.8	96.4	23.6			85.9	6.0	135.2	20.8	114.4	23.2
86.9	6.2	95.1	24.0			90.5	6.5	135.8	21.0	112.9	23.2
90.3	6.6	94.9	24.3			95.8	7.0	136.2	21.2	115.1	23.3
95.7	7.1	93.1	24.6			100.9	7.6	135.7	21.3	113.9	23.4
100.0	7.5	92.8	24.8			106.4	8.3	134.7	21.4	112.2	23.4
105.3	8.5	91.7	25.3			111.7	9.0	133.8	21.4	112.3	23.6
111.0	8.9	91.5	25.5			117.0	9.7	132.4	21.5	111.0	23.6
115.2	9.7	90.9	25.6			118.5	9.9	131.4	21.5	110.7	23.6
121.1	10.8	90.1	26.1			119.0	10.4	130.7	21.5	105.7	24.1
127.7	12.1	90.0	26.4			121.2	10.6	130.0	21.5	101.5	24.5
131.9	13.3	88.5	27.1			122.7	11.3	130.5	21.8	100.7	24.7
136.2	15.5	87.5	27.3			124.4	11.4	128.7	21.8	95.1	25.3
138.0	15.8	86.8	27.5			125.9	11.5	125.3	21.8	91.7	26.4
138.4	15.9	88.3	28.1			126.7	11.7	127.8	21.9	88.8	27.5
139.2	16.1	89.4	28.3			128.8	12.2	126.9	21.9	84.0	28.8
140.4	16.4	90.8	28.7			130.2	12.4	126.2	21.9	78.4	30.7
140.0	16.6	91.8	29.0			131.4	12.5	125.5	21.9	70.3	31.8
140.4	17.0	92.3	29.2			132.4	13.2	125.1	22.0	65.2	32.5
138.0	17.2	94.3	29.8			134.7	13.5	125.6	22.1	62.4	34.0
135.4	17.2	95.2	30.1			134.9	13.7	125.6	22.1	50.3	34.4
133.4	17.2	97.6	30.9			136.5	14.9	124.8	22.2		
131.4	17.9	99.0	31.5			138.4	15.2	123.7	22.2		
130.0	18.0	100.2	32.2			139.4	15.4	119.0	22.2		
132.5	18.1	102.3	34.2			140.2	15.6	123.0	22.3		
133.0	18.3	102.9	36.1			141.0	15.8	121.4	22.4		

Table A2.30. Shear Tests Data for Phase 2: 1% Hemp, at 28 Days.

S1-1%HP-20%coarse						S2-1%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	75.0	13.7	71.0	31.1	0.0	0.0	75.3	9.8	48.3	26.2
0.7	0.0	73.9	14.0	70.9	31.4	0.6	0.0	74.7	10.0	49.4	26.6
2.0	0.4	73.5	14.8	71.2	32.4	1.6	0.1	73.4	10.2	49.3	27.1
3.1	0.7	73.1	17.8	72.4	33.2	3.7	0.2	72.8	10.3	48.9	27.4
4.7	0.8	73.6	19.1	71.9	33.5	4.8	0.3	71.0	11.0	49.0	28.4
5.6	1.0	73.4	19.5	72.5	33.7	4.9	0.3	70.8	11.1	49.0	28.8
6.6	1.0	72.6	19.6	73.3	33.8	5.8	0.3	71.3	11.4	48.2	28.9
7.8	1.1	73.5	19.7	75.7	34.5	6.3	0.3	70.3	11.5	46.5	29.0
8.3	1.1	73.2	19.7	74.7	34.8	7.6	0.4	69.6	11.6	43.2	29.0
9.9	1.2	72.5	19.8	72.9	34.8	8.5	0.4	68.8	12.3	43.8	29.0
15.5	1.5	72.0	20.1	73.6	35.0	9.2	0.5	68.4	12.3	44.5	29.0
20.8	1.7	71.7	20.2	74.8	35.2	10.7	0.5	67.5	12.4	44.7	29.0
26.7	2.1	72.0	20.4	73.9	35.6	15.7	0.8	66.5	13.0		
32.9	2.5	71.0	20.5	73.1	36.3	21.5	1.1	67.3	13.1		
36.3	2.8	71.2	21.0	72.1	36.4	27.6	1.4	66.8	13.2		
38.0	2.9	70.4	21.1	71.7	36.6	34.2	2.0	67.2	13.2		
42.7	3.3	71.9	21.7	70.6	37.0	41.3	2.3	66.4	13.3		
46.6	3.6	71.6	21.8	71.5	37.3	48.1	2.8	67.1	13.4		
52.6	4.2	72.1	22.0	72.5	37.5	50.9	3.1	66.3	14.1		
56.3	4.4	72.6	22.2	73.1	37.9	55.1	3.3	65.9	14.1		
62.6	5.0	71.8	22.3	72.6	38.2	61.1	3.8	65.7	14.5		
68.6	5.5	72.7	22.6	71.7	38.4	67.9	4.3	64.6	14.5		
71.9	5.6	73.1	22.7	70.7	38.5	74.9	5.1	65.1	14.6		
73.6	6.2	73.3	23.0	71.3	38.5	79.1	5.5	66.0	15.4		
74.0	6.3	74.2	23.2	72.1	38.6	81.3	5.6	64.6	15.6		
74.8	6.4	75.3	23.9	73.1	38.7	82.2	6.1	65.0	15.8		
75.6	8.5	75.0	24.2	74.5	39.0	84.4	6.3	64.6	15.9		
77.9	8.6	75.0	24.6	75.1	39.7	85.1	6.5	63.6	16.3		
79.7	8.8	74.8	24.8	76.9	40.4	84.9	6.5	62.6	16.3		
81.1	8.9	75.8	25.3	77.2	40.5	85.0	6.6	63.3	16.9		
82.1	9.1	75.6	25.6	76.3	40.8	83.7	6.6	62.7	17.5		
82.3	9.2	74.9	25.9	77.8	41.1	82.5	6.6	61.6	17.7		
83.5	9.3	74.1	26.1	70.4	41.3	82.0	6.6	60.4	18.3		
84.9	9.6	73.6	26.4	67.7	41.4	80.9	6.6	58.7	18.7		
85.8	9.9	72.9	26.7	69.3	41.4	84.5	7.0	54.2	19.0		
86.2	10.2	71.7	26.9			86.8	7.2	49.5	19.3		
84.5	10.3	72.2	27.1			87.0	7.4	48.9	20.6		
84.8	11.0	71.7	27.6			84.1	8.5	47.9	22.1		
85.0	11.1	71.7	27.9			83.9	8.7	47.7	22.4		
84.5	11.3	71.0	28.6			83.5	8.8	47.9	22.9		
81.8	11.4	71.3	28.9			82.2	9.2	48.2	24.7		
77.6	11.7	70.8	29.1			80.3	9.4	47.8	25.0		
76.0	12.5	70.4	29.7			78.2	9.5	47.9	25.3		
76.1	13.1	70.5	29.9			77.4	9.6	48.3	25.5		
75.1	13.5	71.0	30.3			76.2	9.7	48.0	25.6		

Table A2.31. Bond Tests Data for Phase 2: 1% Hemp, at 28 Days.

B1-1%HP-20%coarse						B2-1%HP-20%coarse					
P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm	P (kN)	mm
0.0	0.0	62.0	7.0	15.0	25.5	0.0	0.0	74.8	9.5	8.3	35.6
0.4	0.1	61.2	7.0	15.9	27.2	0.6	0.0	75.6	9.6	8.2	35.9
0.7	0.1	63.1	7.0	16.1	27.6	2.9	0.1	76.6	9.9	7.4	36.9
0.9	0.2	64.8	7.1	15.3	29.5	4.0	0.1	77.0	10.1	7.3	37.0
2.0	0.5	67.5	7.2	15.1	29.8	4.0	0.1	76.9	10.3	7.2	37.0
3.0	0.8	68.6	7.3	14.8	30.1	5.3	0.2	75.6	10.4	6.6	37.1
3.6	0.9	69.1	7.4	14.6	30.5	7.5	0.2	71.8	10.6		
4.8	1.1	68.2	7.6	14.0	31.0	8.2	0.3	65.1	10.9		
5.4	1.1	65.0	7.8	13.4	31.3	9.0	0.3	48.2	11.6		
6.8	1.2	58.5	8.1	13.0	31.5	10.9	0.4	40.5	12.0		
7.9	1.3	49.7	8.3	12.0	31.7	15.6	0.6	36.6	12.2		
8.7	1.3	41.7	8.5	11.5	32.0	20.3	0.8	35.6	12.4		
9.9	1.4	42.1	8.5	10.4	32.0	26.7	1.1	33.1	12.6		
10.7	1.4	39.0	8.8	9.8	32.0	31.8	1.4	29.9	12.9		
15.0	1.6	37.4	8.9	10.3	32.0	35.6	1.6	27.5	13.2		
20.4	1.8	32.8	9.7	9.7	32.1	36.3	1.8	26.0	13.4		
25.0	2.0	29.0	10.1	10.0	32.1	37.6	1.8	24.9	13.6		
31.3	2.4	26.8	10.3	9.0	32.2	39.4	1.9	24.4	13.8		
37.6	2.7	25.7	10.6	6.4	32.4	40.6	1.9	23.8	14.0		
43.6	3.1	24.9	10.8			41.8	2.0	23.5	14.2		
48.8	3.8	23.1	10.9			43.7	2.2	23.1	14.4		
50.7	3.8	22.7	10.9			45.1	2.3	22.5	14.7		
52.5	4.0	21.6	11.9			46.4	2.3	21.8	15.0		
53.9	4.1	20.6	12.4			47.9	2.5	21.0	15.3		
55.8	4.1	19.1	13.0			49.5	2.6	20.4	15.3		
59.0	4.5	18.6	13.2			50.4	2.6	20.2	15.4		
60.2	4.6	18.0	13.3			52.1	2.7	18.1	15.9		
62.6	4.7	17.8	13.4			53.4	2.9	16.4	17.5		
63.4	5.0	18.0	13.5			54.6	3.0	15.2	18.9		
64.7	5.0	17.2	13.9			55.9	3.1	14.8	19.2		
66.1	5.1	17.3	14.1			57.8	3.3	13.0	20.4		
68.2	5.2	16.8	14.4			59.5	3.4	12.2	21.2		
67.0	5.3	16.6	14.6			60.9	3.5	11.0	21.9		
66.4	5.3	15.1	15.9			62.3	3.5	11.3	22.5		
64.8	5.3	14.7	16.3			63.3	3.8	10.3	23.5		
63.1	5.3	13.8	17.3			64.0	3.8	9.9	23.5		
62.9	5.3	13.7	17.6			65.7	3.9	9.7	23.9		
63.1	5.4	12.8	18.9			67.6	4.1	10.0	24.2		
61.6	5.5	12.9	19.1			66.5	6.4	9.3	25.2		
62.3	5.6	13.0	21.0			69.1	8.2	8.8	25.5		
60.5	5.6	13.0	21.4			68.1	9.2	8.9	25.7		
59.2	6.3	14.0	23.5			69.3	9.2	8.9	26.1		
58.8	6.3	14.0	23.7			71.7	9.3	8.6	31.4		
59.4	6.9	14.7	24.8			72.5	9.3	8.5	31.8		
60.4	7.0	14.9	25.1			71.4	9.4	8.3	35.0		

APPENDIX 3

PHOTOS OF TESTED SPECIMENS OF ALL PHASES AND MISCELLANEOUS PHOTOS

NOTES

For Phase 2 beams photos (Figures A3.1 to A3.18): all cracks without numbers were marked after failure.

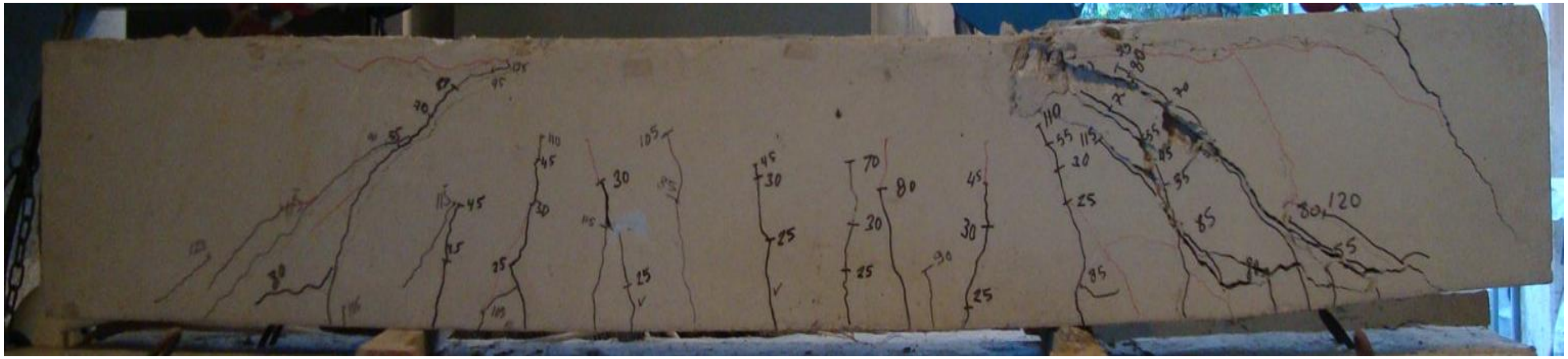


Figure A3.1. Phase 2, Flexure Beam, Control, F1-CL.

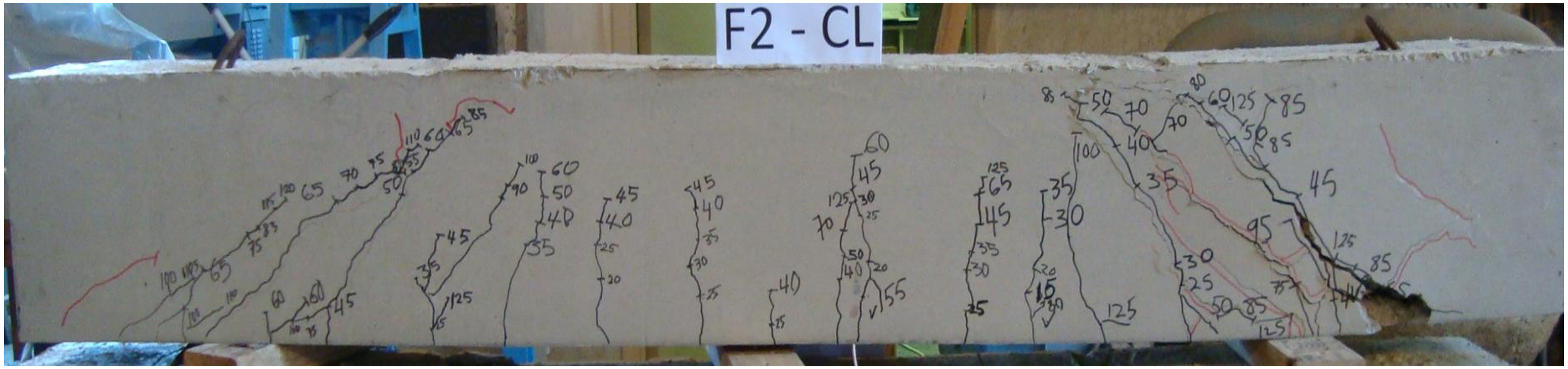


Figure A3.2. Phase 2, Flexure Beam, Control, F2-CL.

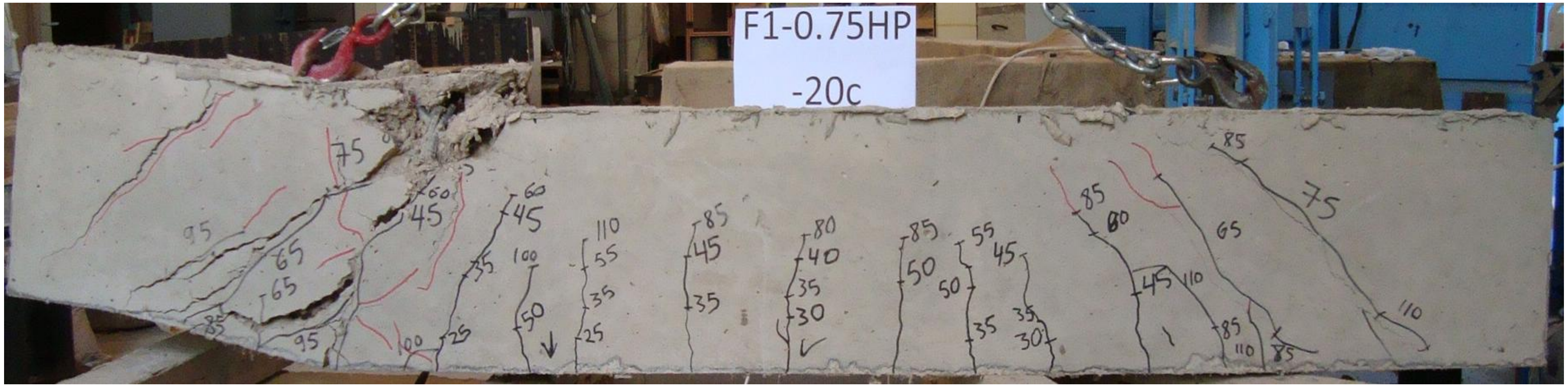


Figure A3.3. Phase 2, Flexure Beam, 0.75%Hemp-20%coarse, F1-0.75%HP-20%c.

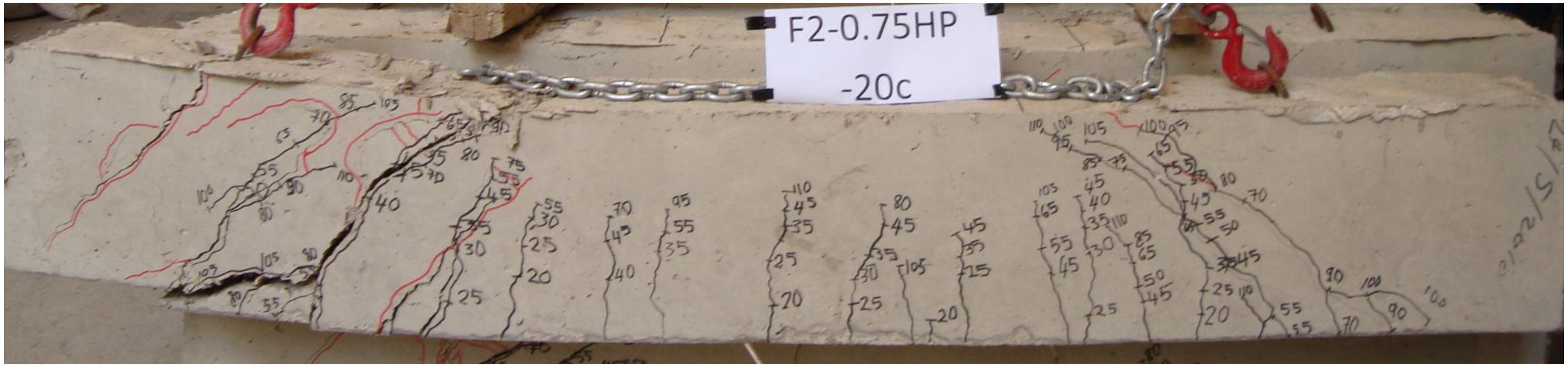


Figure A3.4. Phase 2, Flexure Beam, 0.75%Hemp-20%coarse, F2-0.75%HP-20%c.

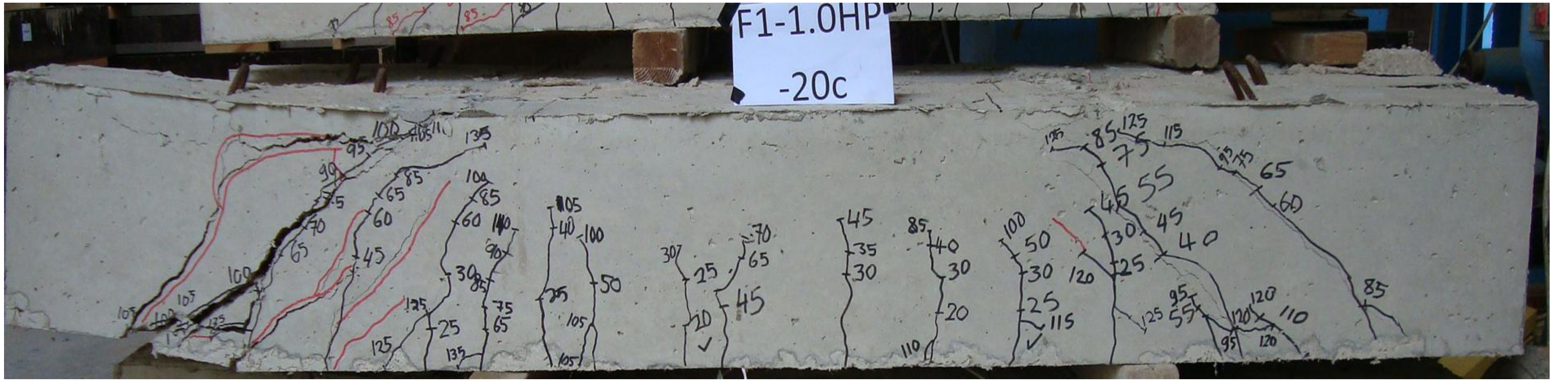


Figure A3.5. Phase 2, Flexure Beam, 1%Hemp-20%coarse, F1-1%HP-20%c.

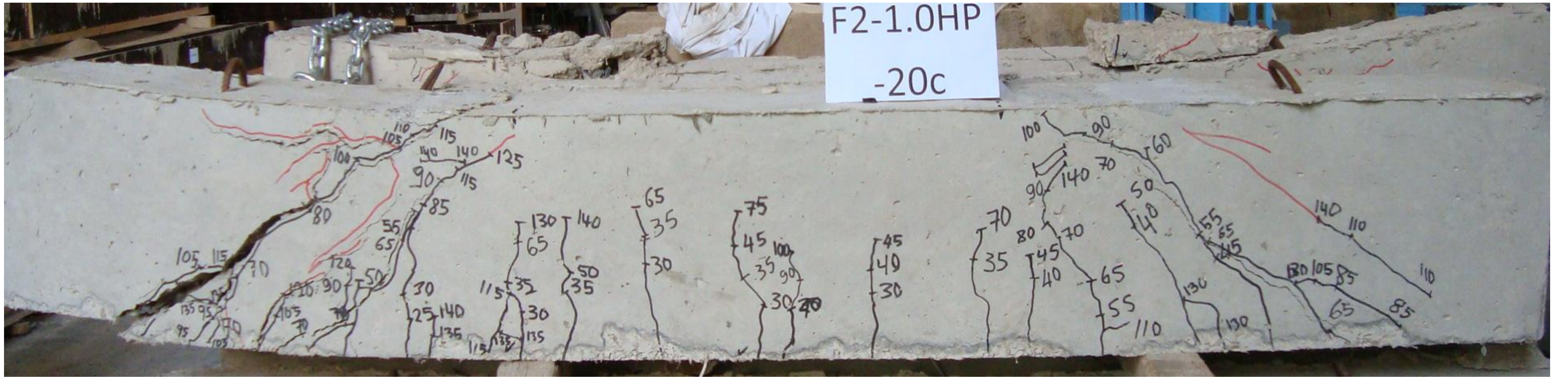


Figure A3.6. Phase 2, Flexure Beam, 1%Hemp-20%coarse, F2-1%HP-20%c.

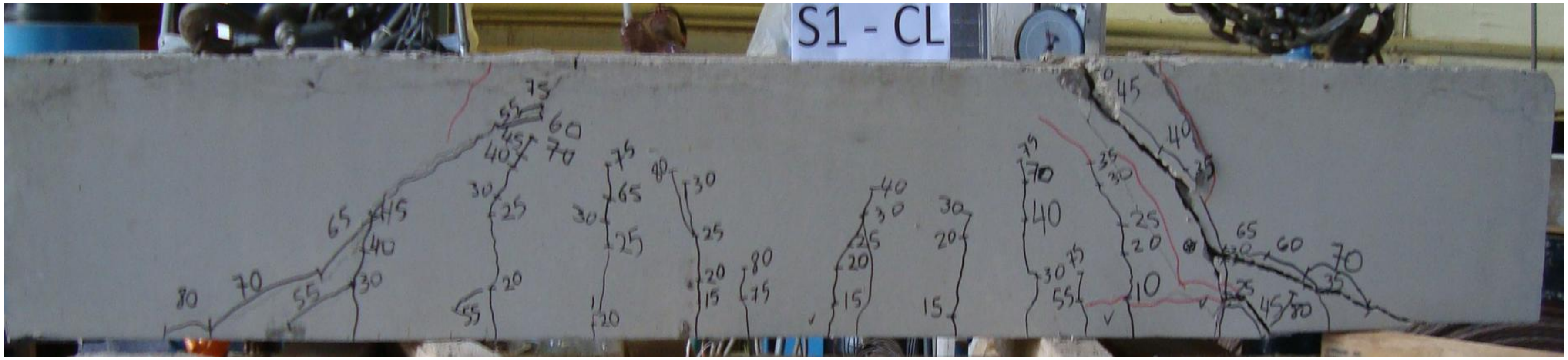


Figure A3.7. Phase 2, Shear Beam, Control, S1-CL.

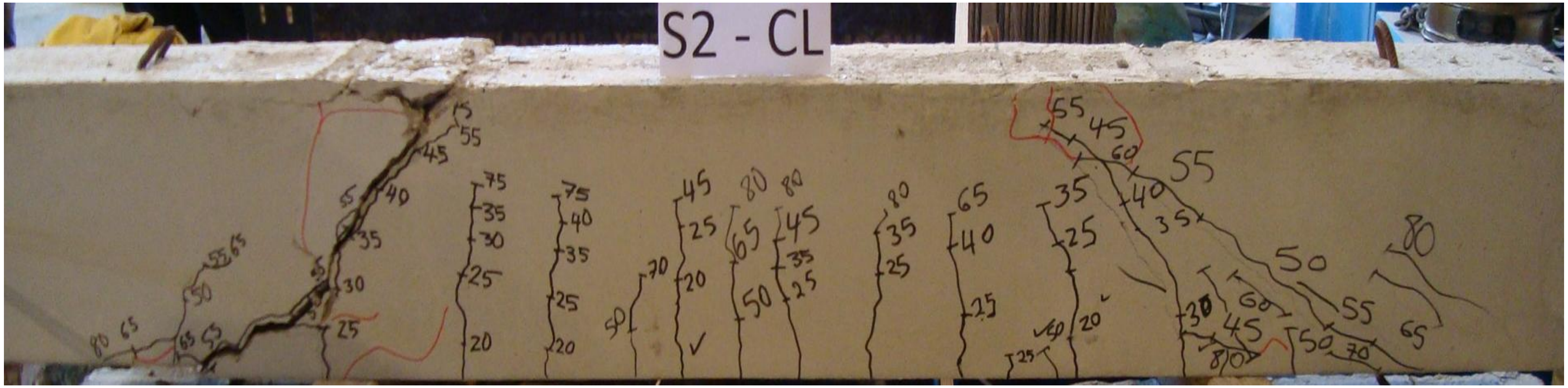


Figure A3.8. Phase 2, Shear Beam, Control, S2-CL.

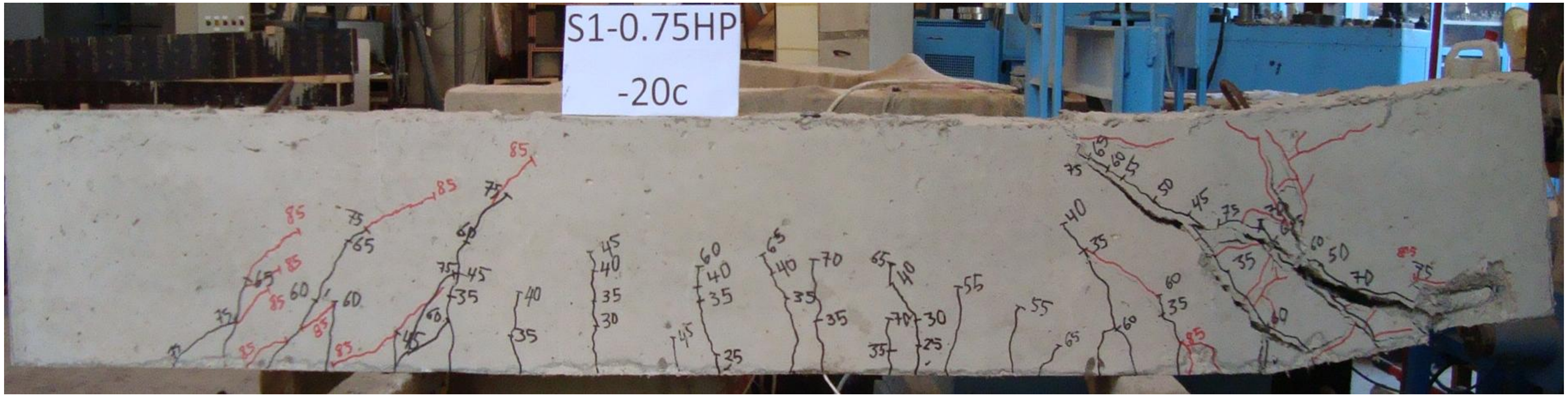


Figure A3.9. Phase 2, Shear Beam, 0.75%Hemp-20%coarse, S1-0.75%HP-20%c.

Figure A3.10. Phase 2, Shear Beam, 0.75%Hemp-20%coarse, S2-0.75%HP-20%c.

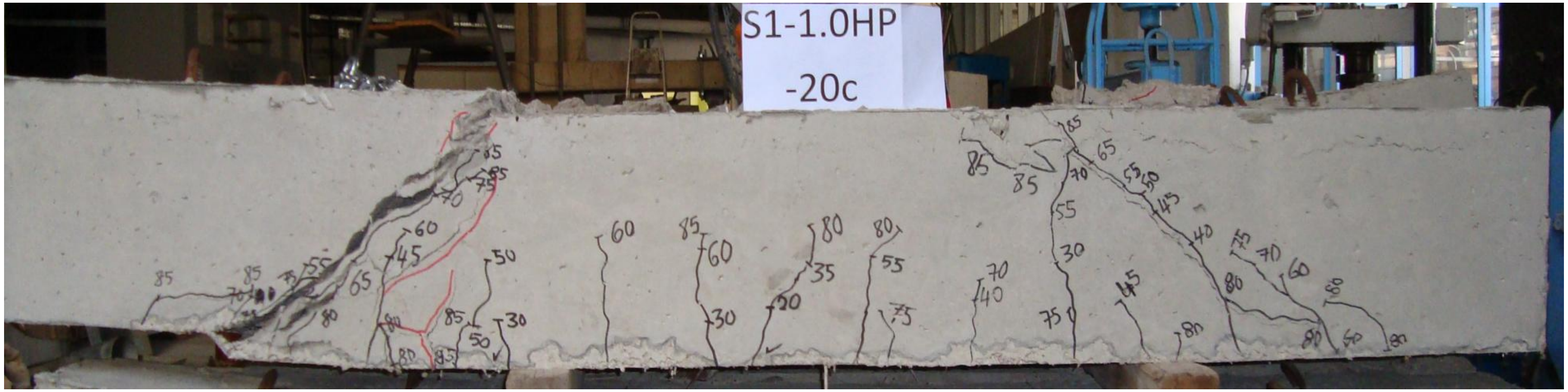


Figure A3.11. Phase 2, Shear Beam, 1%Hemp-20%coarse, S1-1%HP-20%c.

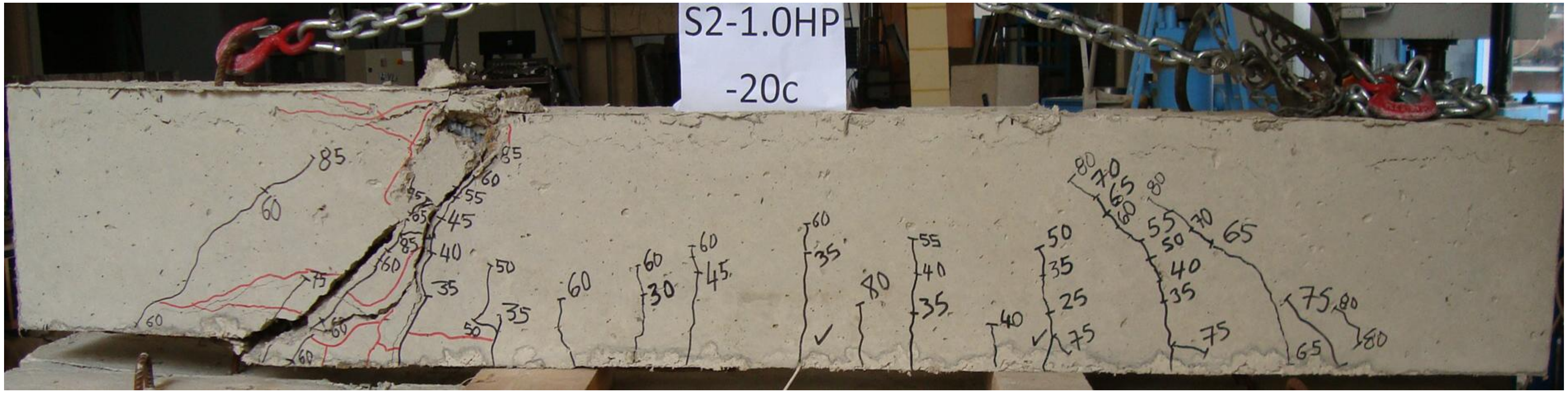


Figure A3.12. Phase 2, Shear Beam, 1%Hemp-20%coarse, S2-1%HP-20%c.

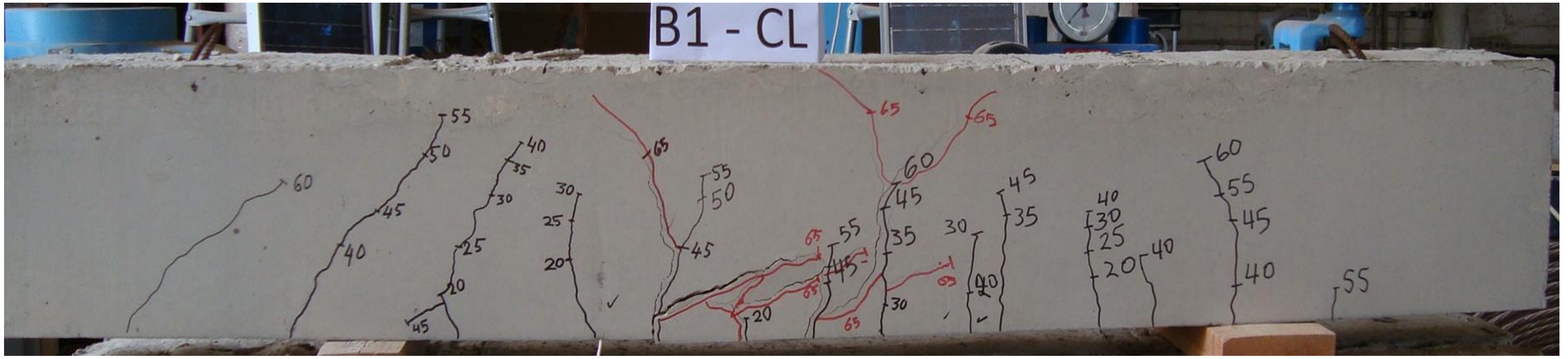


Figure A3.13. Phase 2, Bond Beam, Control, B1-CL.

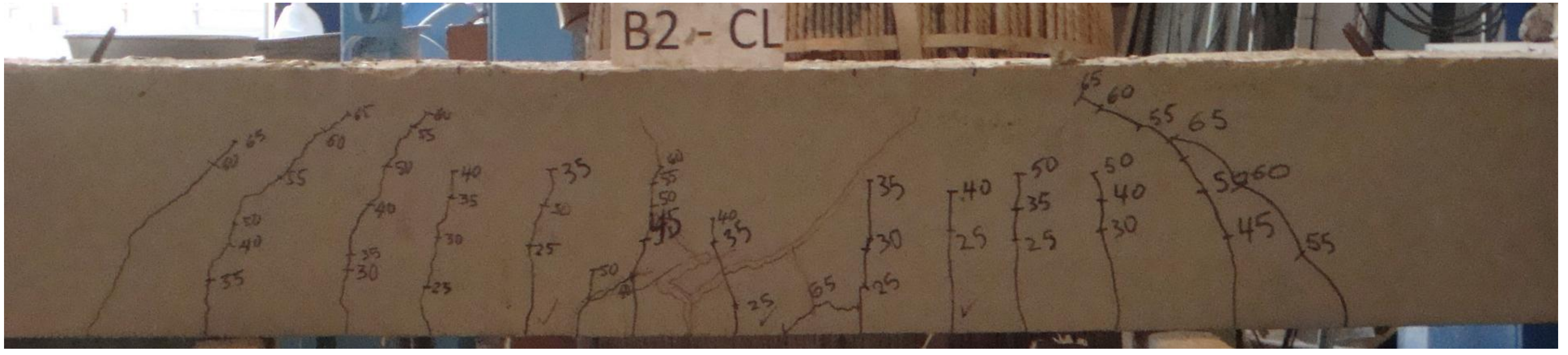


Figure A3.14. Phase 2, Bond Beam, Control, B2-CL.

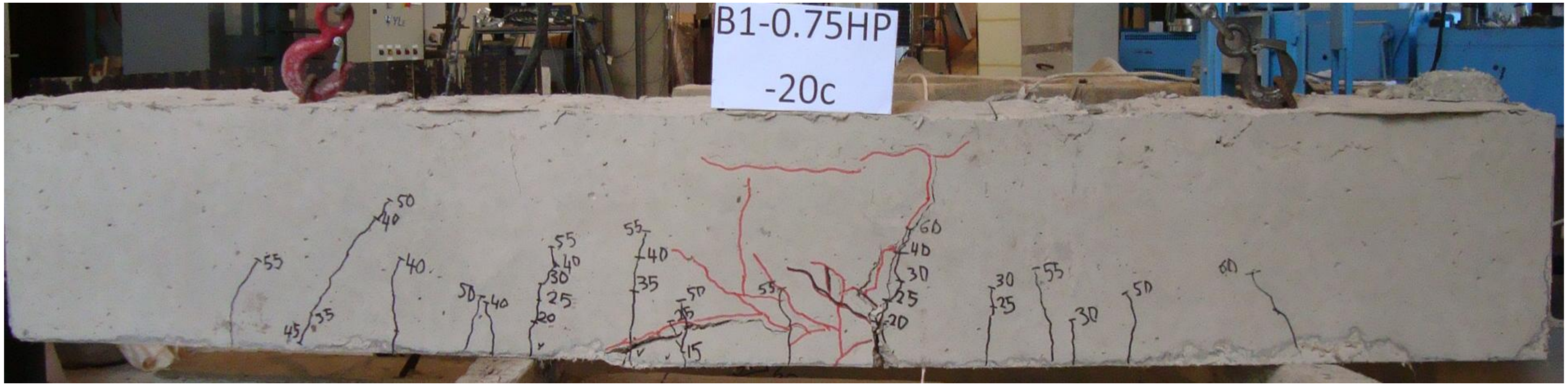


Figure A3.15. Phase 2, Bond Beam, 0.75%Hemp-20%coarse, B1-0.75%HP-20%c.

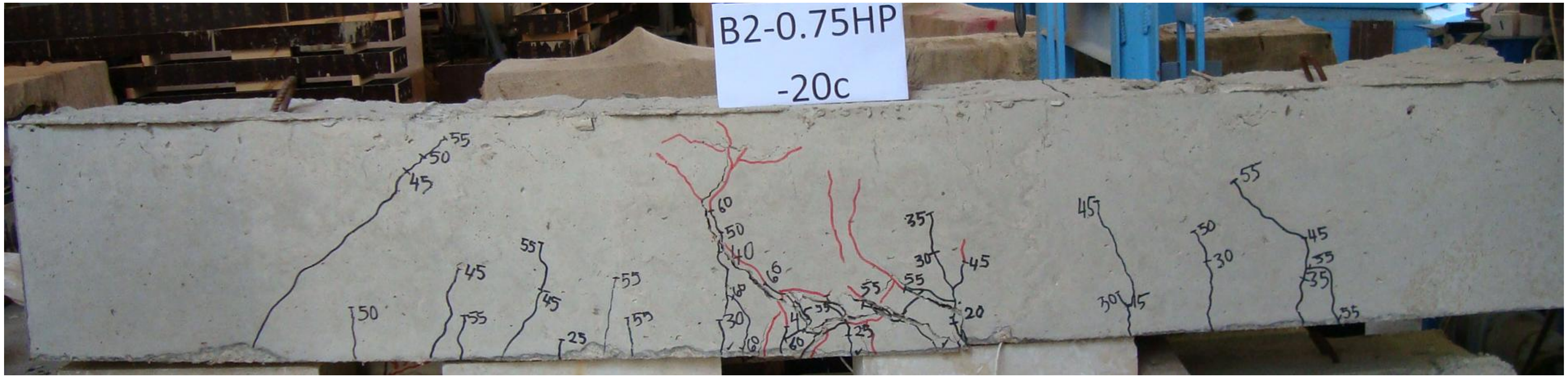


Figure A3.16. Phase 2, Bond Beam, 0.75%Hemp-20%coarse, B2-0.75%HP-20%c.

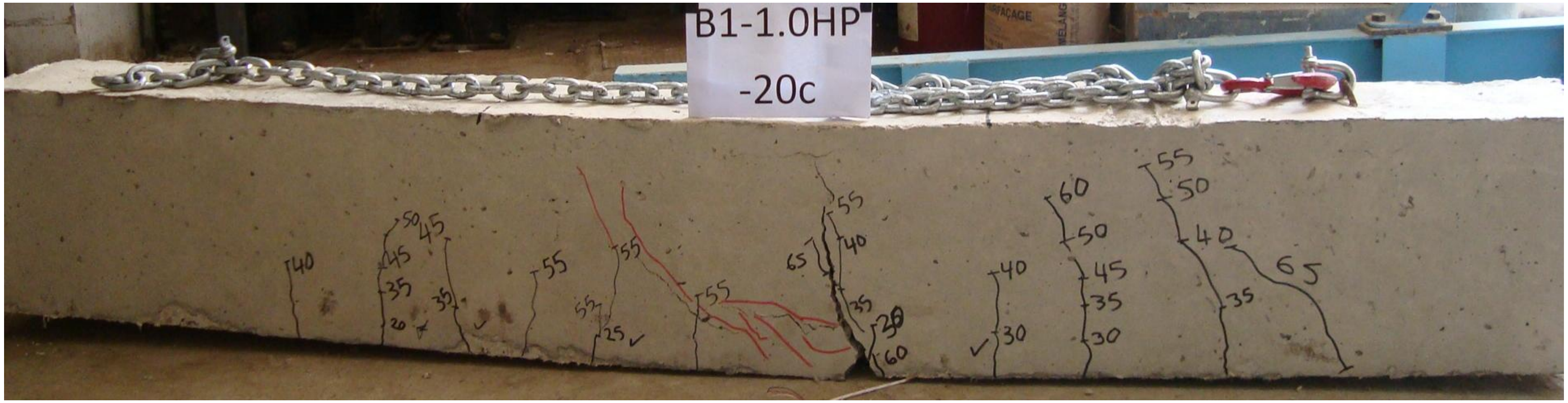


Figure A3.17. Phase 2, Bond Beam, 1%Hemp-20%coarse, B1-1%HP-20%c.

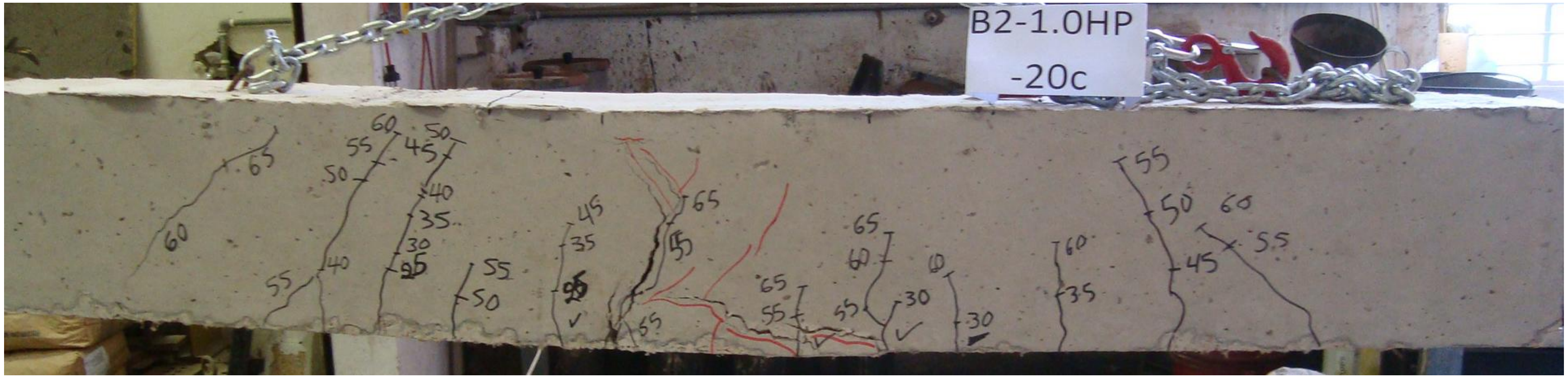


Figure A3.18. Phase 2, Bond Beam, 1%Hemp-20%coarse, B2-1%HP-20%c.

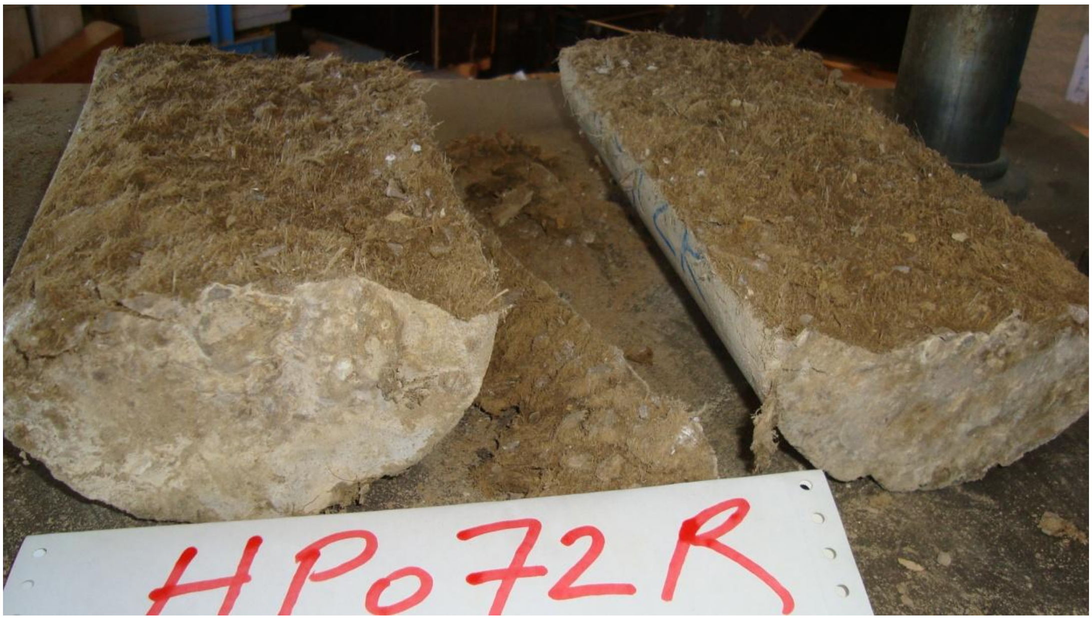


Figure A3.19. Phase 1, Splitting Tensile Tested Sample.

Figure A3.20. Phase 1, Flexure Tested Sample.

Figure A3.21. Phase 1, Compression Tested Sample.

Figure A3.22. Phase 1, Thermal Test Block Sample.

Figure A3.23. Treated Hemp Fibers Ready for Mixing.

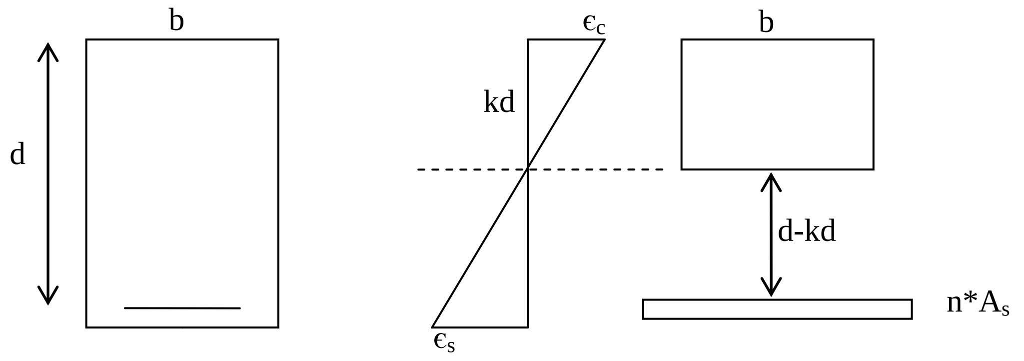
Figure A3.24. Treated Palm Fibers Ready for Mixing.

Figure A3.25. Trial Phase Mixing, Adding Palm Fibers (Wet Mix).

Figure A3.26. Phase 1 Mixing, Hemp Fibers Added on Wet Mix.

Figure A3.27. Phase 2 Mixing, Hemp Fibers Added with Aggregates (Dry Mix) in Ready Mix Plant.

Figure A3.28. Hemp Fibers Preparation, Soaking Panel and Spreading Machine Used After Drying.



F1-CL Beam Calculations (Assumed Elastic Strain)

M_w = P*L/3 with P = 142 kN and L = 1.8 m,
f'_c = 270 kg/cm^2 and E_c = 15,115*sqrt(f'_c) = 248,365 kg/cm^2,
E_s = 2100000 kg/cm^2 and A_s = 6.28 cm^2,
n = E_s/E_c = 8 and k = sqrt[$(\rho*n)^2$ + (2 ρ*n)] – (ρ*n) = 0.37,
I_{cr} = $(b*(kd)^3)/12 + b*(kd)*(kd/2)^2 + n*A_s*(d-kd)^2$ = 18446.8 cm^4,

⇨ $f_s = n*M_w*(d-kd)/I_{cr}$ = 6,178 kg/cm^2

Figure A3.29. Phase 2 Beams Cracked Section Analysis Sample Calculation, F1-CL Beam.

APPENDIX 4

PHASE ONE STATISTICAL ANALYSIS TABLES FOR ONE-WAY AND TWO-WAY ANOVA

NOTES

The units for the tests raw data in the statistical tables are as follows:

Compression Tests: COMP3, COMP7, and COMP28 in kg/cm^2.

Modulus of Rupture Tests: MOR7 and MOR28 Tests in MPa.

Splitting Tensile Test: SPLIT28 in kPa.

Modulus of Elasticity Test: E28 in kg/cm^2.

CR: Coarse Reduction in %.

Table A4.1. One-Way ANOVA Analysis Data Sheet 1.

The SAS System 16:03 Monday, June 28, 2010 90

Obs	TRT	COMP3	COMP7	COMP28	MOR7	MOR28	Split28	E28
1	A	115.9	184.6	257.3	2.6	3.3	2198	231019
2	A	122.0	189.6	209.6	2.5	3.5	2302	244053
3	A	118.1	208.5	234.5	2.6	3.4	2250	237535
4	B	115.9	163.0	201.8	2.7	2.7	1815	214590
5	B	114.2	170.8	205.7	2.5	2.4	1743	221778
6	B	115.0	149.1	203.8	2.6	2.6	1779	218183
7	C	129.2	151.9	170.2	2.3	2.6	2344	225447
8	C	134.2	162.5	214.0	2.4	2.1	2133	214624
9	C	122.0	153.6	184.1	2.3	2.3	2234	220035
10	D	93.1	139.7	174.1	2.3	2.8	1969	184628
11	D	103.7	146.9	175.2	2.0	3.0	2010	194071
12	D	98.3	143.2	174.5	2.2	3.0	1809	189351
13	E	88.7	125.9	166.3	2.2	2.8	1560	188083
14	E	90.4	126.4	167.4	2.0	2.7	1672	157998
15	E	89.4	126.0	166.8	2.1	2.7	1715	173039
16	F	85.4	115.3	182.4	2.2	2.7	1601	225042
17	F	81.5	112.6	173.0	2.3	3.0	1578	205810
18	F	83.4	113.8	177.8	2.2	2.3	1588	215425
19	G	101.5	112.6	207.9	2.3	3.3	1815	144338
20	G	102.0	131.4	194.1	2.7	3.0	1794	154054
21	G	101.6	138.6	201.1	2.8	3.0	1805	149197
22	H	90.4	119.8	171.3	2.2	2.4	2269	220998
23	H	90.9	124.2	170.2	2.3	3.0	2144	192577
24	H	80.4	122.1	170.9	2.3	2.3	2107	206787
25	I	77.6	124.2	169.7	2.4	2.8	2163	163266
26	I	74.3	109.2	189.6	2.3	2.2	2062	159417
27	I	76.0	122.5	177.4	2.4	2.4	2167	161340
28	J	84.8	133.6	191.8	2.6	2.1	2246	189997
29	J	93.7	123.6	185.7	2.2	2.3	2230	189327
30	J	94.3	122.0	188.7	2.0	2.2	2237	189661
31	K	94.8	127.5	164.7	2.4	2.8	2131	175178
32	K	93.7	138.1	179.6	2.3	2.9	2195	164017
33	K	94.4	136.4	200.2	2.4	2.8	2162	169599
34	L	98.7	135.8	166.9	2.9	3.1	2298	162686
35	L	92.0	150.3	168.6	2.9	2.7	2268	179080
36	L	97.0	133.6	167.7	2.9	3.2	2282	170884

Table A4.2. One-Way ANOVA Analysis Data Sheet 2.

--- TRT=A ---

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	118.6666667	3.0892286	115.9000000	122.0000000	1.7835670
COMP7	194.2333333	12.6056865	184.6000000	208.5000000	7.2778965
COMP28	233.8000000	23.8577032	209.6000000	257.3000000	13.7742513
MOR7	2.5666667	0.0577350	2.5000000	2.6000000	0.0333333
MOR28	3.4000000	0.1000000	3.3000000	3.5000000	0.0577350
Split28	2250.00	52.0000000	2198.00	2302.00	30.0222140
E28	237535.67	6517.00	231019.00	244053.00	3762.59

--- TRT=B ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	115.0333333	0.8504901	114.2000000	115.9000000	0.4910307
COMP7	160.9666667	10.9919668	149.1000000	170.8000000	6.3462150
COMP28	203.7666667	1.9502137	201.8000000	205.7000000	1.1259564
MOR7	2.6000000	0.1000000	2.5000000	2.7000000	0.0577350
MOR28	2.5666667	0.1527525	2.4000000	2.7000000	0.0881917
Split28	1779.00	36.0000000	1743.00	1815.00	20.7846097
E28	218183.67	3594.00	214590.00	221778.00	2075.00

--- TRT=C ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	128.4666667	6.1329710	122.0000000	134.2000000	3.5408725
COMP7	156.0000000	5.6929781	151.9000000	162.5000000	3.2868425
COMP28	189.4333333	22.3817634	170.2000000	214.0000000	12.9221171
MOR7	2.3333333	0.0577350	2.3000000	2.4000000	0.0333333
MOR28	2.3333333	0.2516611	2.1000000	2.6000000	0.1452966
Split28	2237.00	105.5319857	2133.00	2344.00	60.9289203
E28	220035.33	5411.50	214624.00	225447.00	3124.33

Table A4.3. One-Way ANOVA Analysis Data Sheet 3.

--- TRT=D ---

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	98.3666667	5.3003145	93.1000000	103.7000000	3.0601380
COMP7	143.2666667	3.6004629	139.7000000	146.9000000	2.0787282
COMP28	174.6000000	0.5567764	174.1000000	175.2000000	0.3214550
MOR7	2.1666667	0.1527525	2.0000000	2.3000000	0.0881917
MOR28	2.9333333	0.1154701	2.8000000	3.0000000	0.0666667
Split28	1929.33	106.2089136	1809.00	2010.00	61.3197449
E28	189350.00	4721.50	184628.00	194071.00	2725.96

--- TRT=E ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	89.5000000	0.8544004	88.7000000	90.4000000	0.4932883
COMP7	126.1000000	0.2645751	125.9000000	126.4000000	0.1527525
COMP28	166.8333333	0.5507571	166.3000000	167.4000000	0.3179797
MOR7	2.1000000	0.1000000	2.0000000	2.2000000	0.0577350
MOR28	2.7333333	0.0577350	2.7000000	2.8000000	0.0333333
Split28	1649.00	80.0187478	1560.00	1715.00	46.1988456
E28	173040.00	15042.50	157998.00	188083.00	8684.79

--- TRT=F ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	83.4333333	1.9502137	81.5000000	85.4000000	1.1259564
COMP7	113.9000000	1.3527749	112.6000000	115.3000000	0.7810250
COMP28	177.7333333	4.7003546	173.0000000	182.4000000	2.7137510
MOR7	2.2333333	0.0577350	2.2000000	2.3000000	0.0333333
MOR28	2.6666667	0.3511885	2.3000000	3.0000000	0.2027588
Split28	1589.00	11.5325626	1578.00	1601.00	6.6583281
E28	215425.67	9616.00	205810.00	225042.00	5551.80

Table A4.4. One-Way ANOVA Analysis Data Sheet 4.

-- TRT=G --

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	101.7000000	0.2645751	101.5000000	102.0000000	0.1527525
COMP7	127.5333333	13.4243560	112.6000000	138.6000000	7.7505555
COMP28	201.0333333	6.9002415	194.1000000	207.9000000	3.9838563
MOR7	2.6000000	0.2645751	2.3000000	2.8000000	0.1527525
MOR28	3.1000000	0.1732051	3.0000000	3.3000000	0.1000000
Split28	1804.67	10.5039675	1794.00	1815.00	6.0644685
E28	149196.33	4858.00	144338.00	154054.00	2804.77

-- TRT=H --

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	87.2333333	5.9231185	80.4000000	90.9000000	3.4197141
COMP7	122.0333333	2.2007574	119.8000000	124.2000000	1.2706079
COMP28	170.8000000	0.5567764	170.2000000	171.3000000	0.3214550
MOR7	2.2666667	0.0577350	2.2000000	2.3000000	0.0333333
MOR28	2.5666667	0.3785939	2.3000000	3.0000000	0.2185813
Split28	2173.33	84.8901251	2107.00	2269.00	49.0113366
E28	206787.33	14210.50	192577.00	220998.00	8204.44

-- TRT=I --

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	75.9666667	1.6502525	74.3000000	77.6000000	0.9527737
COMP7	118.6333333	8.2136066	109.2000000	124.2000000	4.7421280
COMP28	178.9000000	10.0344407	169.7000000	189.6000000	5.7933870
MOR7	2.3666667	0.0577350	2.3000000	2.4000000	0.0333333
MOR28	2.4666667	0.3055050	2.2000000	2.8000000	0.1763834
Split28	2130.67	59.5007003	2062.00	2167.00	34.3527453
E28	161341.00	1924.50	159417.00	163266.00	1111.11

Table A4.5. One-Way ANOVA Analysis Data Sheet 5.

--- TRT=J ---

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	90.9333333	5.3200877	84.8000000	94.3000000	3.0715541
COMP7	126.4000000	6.2864935	122.0000000	133.6000000	3.6295087
COMP28	188.7333333	3.0501366	185.7000000	191.8000000	1.7609972
MOR7	2.2666667	0.3055050	2.0000000	2.6000000	0.1763834
MOR28	2.2000000	0.1000000	2.1000000	2.3000000	0.0577350
Split28	2237.67	8.0208063	2230.00	2246.00	4.6308147
E28	189661.67	335.0004975	189327.00	189997.00	193.4126274

--- TRT=K ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	94.3000000	0.5567764	93.7000000	94.8000000	0.3214550
COMP7	134.0000000	5.6929781	127.5000000	138.1000000	3.2868425
COMP28	181.5000000	17.8261045	164.7000000	200.2000000	10.2919062
MOR7	2.3666667	0.0577350	2.3000000	2.4000000	0.0333333
MOR28	2.8333333	0.0577350	2.8000000	2.9000000	0.0333333
Split28	2162.67	32.0052079	2131.00	2195.00	18.4782154
E28	169598.00	5580.50	164017.00	175178.00	3221.90

--- TRT=L ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
COMP3	95.9000000	3.4828150	92.0000000	98.7000000	2.0108042
COMP7	139.9000000	9.0735880	133.6000000	150.3000000	5.2386385
COMP28	167.7333333	0.8504901	166.9000000	168.6000000	0.4910307
MOR7	2.9000000	0	2.9000000	2.9000000	0
MOR28	3.0000000	0.2645751	2.7000000	3.2000000	0.1527525
Split28	2282.67	15.0111070	2268.00	2298.00	8.6666667
E28	170883.33	8197.00	162686.00	179080.00	4732.54

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The GLM Procedure

Class Level Information

Class	Levels	Values
TRT	12	A B C D E F G H I J K L

Number of Observations Read 36
Number of Observations Used 36

Table A4.6. One-Way ANOVA Analysis Data Sheet 6.

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The GLM Procedure

Dependent Variable: COMP3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	7836.394167	712.399470	53.72	<.0001
Error	24	318.253333	13.260556		
Corrected Total	35	8154.647500			

R-Square	Coeff Var	Root MSE	COMP3 Mean
0.960973	3.704795	3.641505	98.29167

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	7836.394167	712.399470	53.72	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	7836.394167	712.399470	53.72	<.0001

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The GLM Procedure

Dependent Variable: COMP7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	16960.47639	1541.86149	25.22	<.0001
Error	24	1467.56000	61.14833		
Corrected Total	35	18428.03639			

R-Square	Coeff Var	Root MSE	COMP7 Mean
0.920363	5.642740	7.819740	138.5806

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	16960.47639	1541.86149	25.22	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	16960.47639	1541.86149	25.22	<.0001

Table A4.7. One-Way ANOVA Analysis Data Sheet 7.

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The GLM Procedure

Dependent Variable: COMP28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	12138.29889	1103.48172	8.42	<.0001
Error	24	3146.10667	131.08778		
Corrected Total	35	15284.40556			

R-Square	Coeff Var	Root MSE	COMP28 Mean
0.794162	6.147673	11.44936	186.2389

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	12138.29889	1103.48172	8.42	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	12138.29889	1103.48172	8.42	<.0001

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The GLM Procedure

Dependent Variable: MOR7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	1.71638889	0.15603535	8.26	<.0001
Error	24	0.45333333	0.01888889		
Corrected Total	35	2.16972222			

R-Square	Coeff Var	Root MSE	MOR7 Mean
0.791064	5.733171	0.137437	2.397222

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	1.71638889	0.15603535	8.26	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	1.71638889	0.15603535	8.26	<.0001

Table A4.8. One-Way ANOVA Analysis Data Sheet 8.

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The GLM Procedure

Dependent Variable: MOR28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	3.82666667	0.34787879	7.12	<.0001
Error	24	1.17333333	0.04888889		
Corrected Total	35	5.00000000			

R-Square	Coeff Var	Root MSE	MOR28 Mean
0.765333	8.089329	0.221108	2.733333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	3.82666667	0.34787879	7.12	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	3.82666667	0.34787879	7.12	<.0001

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The GLM Procedure

Dependent Variable: Split28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	2125580.083	193234.553	51.39	<.0001
Error	24	90248.667	3760.361		
Corrected Total	35	2215828.750			

R-Square	Coeff Var	Root MSE	Split28 Mean
0.959271	3.037612	61.32178	2018.750

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	2125580.083	193234.553	51.39	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	2125580.083	193234.553	51.39	<.0001

Table A4.9. One-Way ANOVA Analysis Data Sheet 9.

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The GLM Procedure

Dependent Variable: E28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	25210861496	2291896500	36.51	<.0001
Error	24	1506792951	62783040		
Corrected Total	35	26717654447			

R-Square	Coeff Var	Root MSE	E28 Mean
0.943603	4.132174	7923.575	191753.2

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRT	11	25210861496	2291896500	36.51	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	11	25210861496	2291896500	36.51	<.0001

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The GLM Procedure

Dunnett's t Tests for COMP3

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	13.26056
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	8.824

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
C - A	9.800	0.976	18.624	***
B - A	-3.633	-12.457	5.191	
G - A	-16.967	-25.791	-8.143	***
D - A	-20.300	-29.124	-11.476	***
L - A	-22.767	-31.591	-13.943	***
K - A	-24.367	-33.191	-15.543	***
J - A	-27.733	-36.557	-18.909	***
E - A	-29.167	-37.991	-20.343	***
H - A	-31.433	-40.257	-22.609	***
F - A	-35.233	-44.057	-26.409	***
I - A	-42.700	-51.524	-33.876	***

Table A4.10. One-Way ANOVA Analysis Data Sheet 10.

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The GLM Procedure

Dunnett's t Tests for COMP7

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	61.14833
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	18.949

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
B - A	-33.267	-52.215	-14.318	***
C - A	-38.233	-57.182	-19.285	***
D - A	-50.967	-69.915	-32.018	***
L - A	-54.333	-73.282	-35.385	***
K - A	-60.233	-79.182	-41.285	***
G - A	-66.700	-85.649	-47.751	***
J - A	-67.833	-86.782	-48.885	***
E - A	-68.133	-87.082	-49.185	***
H - A	-72.200	-91.149	-53.251	***
I - A	-75.600	-94.549	-56.651	***
F - A	-80.333	-99.282	-61.385	***

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The GLM Procedure

Dunnett's t Tests for COMP28

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	131.0878
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	27.744

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
B - A	-30.033	-57.777	-2.289	***
G - A	-32.767	-60.511	-5.023	***
C - A	-44.367	-72.111	-16.623	***
J - A	-45.067	-72.811	-17.323	***
K - A	-52.300	-80.044	-24.556	***
I - A	-54.900	-82.644	-27.156	***
F - A	-56.067	-83.811	-28.323	***
D - A	-59.200	-86.944	-31.456	***
H - A	-63.000	-90.744	-35.256	***
L - A	-66.067	-93.811	-38.323	***
E - A	-66.967	-94.711	-39.223	***

Table A4.11. One-Way ANOVA Analysis Data Sheet 11.

The GLM Procedure

Dunnett's t Tests for MOR7

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	0.018889
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	0.333

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
L - A	0.3333	0.0003	0.6664	***
G - A	0.0333	-0.2997	0.3664	
B - A	0.0333	-0.2997	0.3664	
I - A	-0.2000	-0.5330	0.1330	
K - A	-0.2000	-0.5330	0.1330	
C - A	-0.2333	-0.5664	0.0997	
J - A	-0.3000	-0.6330	0.0330	
H - A	-0.3000	-0.6330	0.0330	
F - A	-0.3333	-0.6664	-0.0003	***
D - A	-0.4000	-0.7330	-0.0670	***
E - A	-0.4667	-0.7997	-0.1336	***

The GLM Procedure

Dunnett's t Tests for MOR28

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	0.048889
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	0.5358

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
G - A	-0.3000	-0.8358	0.2358	
L - A	-0.4000	-0.9358	0.1358	
D - A	-0.4667	-1.0025	0.0691	
K - A	-0.5667	-1.1025	-0.0309	***
E - A	-0.6667	-1.2025	-0.1309	***
F - A	-0.7333	-1.2691	-0.1975	***
H - A	-0.8333	-1.3691	-0.2975	***
B - A	-0.8333	-1.3691	-0.2975	***
I - A	-0.9333	-1.4691	-0.3975	***
C - A	-1.0667	-1.6025	-0.5309	***
J - A	-1.2000	-1.7358	-0.6642	***

Table A4.12. One-Way ANOVA Analysis Data Sheet 12.

The GLM Procedure

Dunnett's t Tests for Split28

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	3760.361
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	148.59

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
L - A	32.67	-115.93	181.26	
J - A	-12.33	-160.93	136.26	
C - A	-13.00	-161.59	135.59	
H - A	-76.67	-225.26	71.93	
K - A	-87.33	-235.93	61.26	
I - A	-119.33	-267.93	29.26	
D - A	-320.67	-469.26	-172.07	***
G - A	-445.33	-593.93	-296.74	***
B - A	-471.00	-619.59	-322.41	***
E - A	-601.00	-749.59	-452.41	***
F - A	-661.00	-809.59	-512.41	***

The GLM Procedure

Dunnett's t Tests for E28

NOTE: This test controls the Type I experimentwise error for comparisons of all treatments against a control.

Alpha	0.05
Error Degrees of Freedom	24
Error Mean Square	62783040
Critical Value of Dunnett's t	2.96778
Minimum Significant Difference	19200

Comparisons significant at the 0.05 level are indicated by ***.

TRT Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
C - A	-17500	-36701	1700	
B - A	-19352	-38552	-152	***
F - A	-22110	-41310	-2910	***
H - A	-30748	-49949	-11548	***
J - A	-47874	-67074	-28674	***
D - A	-48186	-67386	-28985	***
E - A	-64496	-83696	-45295	***
L - A	-66652	-85853	-47452	***
K - A	-67938	-87138	-48737	***
I - A	-76195	-95395	-56994	***
G - A	-88339	-107540	-69139	***

Table A4.13. One-Way ANOVA Analysis Data Sheet 13.

The GLM Procedure
Least Squares Means

TRT	COMP3 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	118.666667	2.102424	<.0001	1
B	115.033333	2.102424	<.0001	2
C	128.466667	2.102424	<.0001	3
D	98.366667	2.102424	<.0001	4
E	89.500000	2.102424	<.0001	5
F	83.433333	2.102424	<.0001	6
G	101.700000	2.102424	<.0001	7
H	87.233333	2.102424	<.0001	8
I	75.966667	2.102424	<.0001	9
J	90.933333	2.102424	<.0001	10
K	94.300000	2.102424	<.0001	11
L	95.900000	2.102424	<.0001	12

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP3

i/j	1	2	3	4	5	6
1		0.2336	0.0030	<.0001	<.0001	<.0001
2	0.2336		0.0001	<.0001	<.0001	<.0001
3	0.0030	0.0001		<.0001	<.0001	<.0001
4	<.0001	<.0001	<.0001		0.0065	<.0001
5	<.0001	<.0001	<.0001	0.0065		0.0525
6	<.0001	<.0001	<.0001	<.0001	0.0525	
7	<.0001	0.0002	<.0001	0.2733	0.0004	<.0001
8	<.0001	<.0001	<.0001	0.0010	0.4533	0.2135
9	<.0001	<.0001	<.0001	<.0001	0.0001	0.0192
10	<.0001	<.0001	<.0001	0.0197	0.6341	0.0187
11	<.0001	<.0001	<.0001	0.1841	0.1195	0.0013
12	<.0001	<.0001	<.0001	0.4149	0.0416	0.0003

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP3

i/j	7	8	9	10	11	12
1	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
2	0.0002	<.0001	<.0001	<.0001	<.0001	<.0001
3	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
4	0.2733	0.0010	<.0001	0.0197	0.1841	0.4149
5	0.0004	0.4533	0.0001	0.6341	0.1195	0.0416
6	<.0001	0.2135	0.0192	0.0187	0.0013	0.0003

Table A4.14. One-Way ANOVA Analysis Data Sheet 14.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP3

i/j	7	8	9	10	11	12
7		<.0001	<.0001	0.0014	0.0201	0.0629
8	<.0001		0.0009	0.2254	0.0258	0.0076
9	<.0001	0.0009		<.0001	<.0001	<.0001
10	0.0014	0.2254	<.0001		0.2687	0.1078
11	0.0201	0.0258	<.0001	0.2687		0.5954
12	0.0629	0.0076	<.0001	0.1078	0.5954	

TRT	COMP7 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	194.233333	4.514729	<.0001	1
B	160.966667	4.514729	<.0001	2
C	156.000000	4.514729	<.0001	3
D	143.266667	4.514729	<.0001	4
E	126.100000	4.514729	<.0001	5
F	113.900000	4.514729	<.0001	6
G	127.533333	4.514729	<.0001	7
H	122.033333	4.514729	<.0001	8
I	118.633333	4.514729	<.0001	9
J	126.400000	4.514729	<.0001	10
K	134.000000	4.514729	<.0001	11
L	139.900000	4.514729	<.0001	12

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP7

i/j	1	2	3	4	5	6
1		<.0001	<.0001	<.0001	<.0001	<.0001
2	<.0001		0.4442	0.0106	<.0001	<.0001
3	<.0001	0.4442		0.0576	<.0001	<.0001
4	<.0001	0.0106	0.0576		0.0128	0.0001
5	<.0001	<.0001	<.0001	0.0128		0.0680
6	<.0001	<.0001	<.0001	0.0001	0.0680	
7	<.0001	<.0001	0.0002	0.0213	0.8243	0.0431
8	<.0001	<.0001	<.0001	0.0028	0.5302	0.2149
9	<.0001	<.0001	<.0001	0.0008	0.2537	0.4657
10	<.0001	<.0001	0.0001	0.0143	0.9629	0.0620
11	<.0001	0.0003	0.0021	0.1596	0.2279	0.0044

Table A4.15. One-Way ANOVA Analysis Data Sheet 15.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP7

i/j	1	2	3	4	5	6
12	<.0001	0.0030	0.0187	0.6028	0.0409	0.0004

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP7

i/j	7	8	9	10	11	12
1	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
2	<.0001	<.0001	<.0001	<.0001	0.0003	0.0030
3	0.0002	<.0001	<.0001	0.0001	0.0021	0.0187
4	0.0213	0.0028	0.0008	0.0143	0.1596	0.6028
5	0.8243	0.5302	0.2537	0.9629	0.2279	0.0409
6	0.0431	0.2149	0.4657	0.0620	0.0044	0.0004
7		0.3975	0.1761	0.8606	0.3212	0.0646
8	0.3975		0.5993	0.5006	0.0731	0.0100
9	0.1761	0.5993		0.2356	0.0241	0.0028
10	0.8606	0.5006	0.2356		0.2456	0.0451
11	0.3212	0.0731	0.0241	0.2456		0.3646
12	0.0646	0.0100	0.0028	0.0451	0.3646	

TRT	COMP28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	233.800000	6.610289	<.0001	1
B	203.766667	6.610289	<.0001	2
C	189.433333	6.610289	<.0001	3
D	174.600000	6.610289	<.0001	4
E	166.833333	6.610289	<.0001	5
F	177.733333	6.610289	<.0001	6
G	201.033333	6.610289	<.0001	7
H	170.800000	6.610289	<.0001	8
I	178.900000	6.610289	<.0001	9
J	188.733333	6.610289	<.0001	10
K	181.500000	6.610289	<.0001	11
L	167.733333	6.610289	<.0001	12

Table A4.16. One-Way ANOVA Analysis Data Sheet 16.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP28

i/j	1	2	3	4	5	6
1		0.0037	<.0001	<.0001	<.0001	<.0001
2	0.0037		0.1383	0.0047	0.0006	0.0103
3	<.0001	0.1383		0.1257	0.0236	0.2228
4	<.0001	0.0047	0.1257		0.4143	0.7404
5	<.0001	0.0006	0.0236	0.4143		0.2551
6	<.0001	0.0103	0.2228	0.7404	0.2551	
7	0.0018	0.7725	0.2267	0.0093	0.0012	0.0200
8	<.0001	0.0017	0.0577	0.6880	0.6751	0.4655
9	<.0001	0.0137	0.2710	0.6497	0.2091	0.9017
10	<.0001	0.1209	0.9409	0.1436	0.0278	0.2509
11	<.0001	0.0255	0.4045	0.4676	0.1298	0.6906
12	<.0001	0.0008	0.0291	0.4697	0.9241	0.2954

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP28

i/j	7	8	9	10	11	12
1	0.0018	<.0001	<.0001	<.0001	<.0001	<.0001
2	0.7725	0.0017	0.0137	0.1209	0.0255	0.0008
3	0.2267	0.0577	0.2710	0.9409	0.4045	0.0291
4	0.0093	0.6880	0.6497	0.1436	0.4676	0.4697
5	0.0012	0.6751	0.2091	0.0278	0.1298	0.9241
6	0.0200	0.4655	0.9017	0.2509	0.6906	0.2954
7		0.0035	0.0263	0.2007	0.0474	0.0016
8	0.0035		0.3948	0.0670	0.2637	0.7457
9	0.0263	0.3948		0.3033	0.7833	0.2440
10	0.2007	0.0670	0.3033		0.4466	0.0342
11	0.0474	0.2637	0.7833	0.4466		0.1538
12	0.0016	0.7457	0.2440	0.0342	0.1538	

TRT	MOR7 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	2.56666667	0.07934920	<.0001	1
B	2.60000000	0.07934920	<.0001	2
C	2.33333333	0.07934920	<.0001	3
D	2.16666667	0.07934920	<.0001	4
E	2.10000000	0.07934920	<.0001	5
F	2.23333333	0.07934920	<.0001	6

Table A4.17. One-Way ANOVA Analysis Data Sheet 17.

The GLM Procedure
Least Squares Means

TRT	MOR7 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
G	2.60000000	0.07934920	<.0001	7
H	2.26666667	0.07934920	<.0001	8
I	2.36666667	0.07934920	<.0001	9
J	2.26666667	0.07934920	<.0001	10
K	2.36666667	0.07934920	<.0001	11
L	2.90000000	0.07934920	<.0001	12

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR7

i/j	1	2	3	4	5	6
1		0.7690	0.0484	0.0016	0.0004	0.0067
2	0.7690		0.0258	0.0007	0.0002	0.0033
3	0.0484	0.0258		0.1505	0.0484	0.3817
4	0.0016	0.0007	0.1505		0.5580	0.5580
5	0.0004	0.0002	0.0484	0.5580		0.2464
6	0.0067	0.0033	0.3817	0.5580	0.2464	
7	0.7690	1.0000	0.0258	0.0007	0.0002	0.0033
8	0.0133	0.0067	0.5580	0.3817	0.1505	0.7690
9	0.0874	0.0484	0.7690	0.0874	0.0258	0.2464
10	0.0133	0.0067	0.5580	0.3817	0.1505	0.7690
11	0.0874	0.0484	0.7690	0.0874	0.0258	0.2464

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR7

i/j	7	8	9	10	11	12
1	0.7690	0.0133	0.0874	0.0133	0.0874	0.0067
2	1.0000	0.0067	0.0484	0.0067	0.0484	0.0133
3	0.0258	0.5580	0.7690	0.5580	0.7690	<.0001
4	0.0007	0.3817	0.0874	0.3817	0.0874	<.0001
5	0.0002	0.1505	0.0258	0.1505	0.0258	<.0001
6	0.0033	0.7690	0.2464	0.7690	0.2464	<.0001
7		0.0067	0.0484	0.0067	0.0484	0.0133
8	0.0067		0.3817	1.0000	0.3817	<.0001
9	0.0484	0.3817		0.3817	1.0000	<.0001
10	0.0067	1.0000	0.3817		0.3817	<.0001
11	0.0484	0.3817	1.0000	0.3817		<.0001

Table A4.18. One-Way ANOVA Analysis Data Sheet 18.

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The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR7

i/j	1	2	3	4	5	6
12	0.0067	0.0133	<.0001	<.0001	<.0001	<.0001

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR7

i/j	7	8	9	10	11	12
12	0.0133	<.0001	<.0001	<.0001	<.0001	

TRT	MOR28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	3.40000000	0.12765695	<.0001	1
B	2.56666667	0.12765695	<.0001	2
C	2.33333333	0.12765695	<.0001	3
D	2.93333333	0.12765695	<.0001	4
E	2.73333333	0.12765695	<.0001	5
F	2.66666667	0.12765695	<.0001	6
G	3.10000000	0.12765695	<.0001	7
H	2.56666667	0.12765695	<.0001	8
I	2.46666667	0.12765695	<.0001	9
J	2.20000000	0.12765695	<.0001	10
K	2.83333333	0.12765695	<.0001	11
L	3.00000000	0.12765695	<.0001	12

Table A4.19. One-Way ANOVA Analysis Data Sheet 19.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR28

i/j	1	2	3	4	5	6
1		0.0001	<.0001	0.0162	0.0011	0.0005
2	0.0001		0.2085	0.0535	0.3651	0.5848
3	<.0001	0.2085		0.0028	0.0365	0.0772
4	0.0162	0.0535	0.0028		0.2789	0.1527
5	0.0011	0.3651	0.0365	0.2789		0.7152
6	0.0005	0.5848	0.0772	0.1527	0.7152	
7	0.1096	0.0069	0.0003	0.3651	0.0535	0.0245
8	0.0001	1.0000	0.2085	0.0535	0.3651	0.5848
9	<.0001	0.5848	0.4673	0.0162	0.1527	0.2789
10	<.0001	0.0535	0.4673	0.0005	0.0069	0.0162
11	0.0045	0.1527	0.0107	0.5848	0.5848	0.3651
12	0.0365	0.0245	0.0011	0.7152	0.1527	0.0772

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR28

i/j	7	8	9	10	11	12
1	0.1096	0.0001	<.0001	<.0001	0.0045	0.0365
2	0.0069	1.0000	0.5848	0.0535	0.1527	0.0245
3	0.0003	0.2085	0.4673	0.4673	0.0107	0.0011
4	0.3651	0.0535	0.0162	0.0005	0.5848	0.7152
5	0.0535	0.3651	0.1527	0.0069	0.5848	0.1527
6	0.0245	0.5848	0.2789	0.0162	0.3651	0.0772
7		0.0069	0.0018	<.0001	0.1527	0.5848
8	0.0069		0.5848	0.0535	0.1527	0.0245
9	0.0018	0.5848		0.1527	0.0535	0.0069
10	<.0001	0.0535	0.1527		0.0018	0.0002
11	0.1527	0.1527	0.0535	0.0018		0.3651
12	0.5848	0.0245	0.0069	0.0002	0.3651	

TRT	Split28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	2250.00000	35.40415	<.0001	1
B	1779.00000	35.40415	<.0001	2
C	2237.00000	35.40415	<.0001	3
D	1929.33333	35.40415	<.0001	4
E	1649.00000	35.40415	<.0001	5
F	1589.00000	35.40415	<.0001	6

Table A4.20. One-Way ANOVA Analysis Data Sheet 20.

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The GLM Procedure
Least Squares Means

TRT	Split28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
G	1804.66667	35.40415	<.0001	7
H	2173.33333	35.40415	<.0001	8
I	2130.66667	35.40415	<.0001	9
J	2237.66667	35.40415	<.0001	10
K	2162.66667	35.40415	<.0001	11
L	2282.66667	35.40415	<.0001	12

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Split28

i/j	1	2	3	4	5	6
1		<.0001	0.7974	<.0001	<.0001	<.0001
2	<.0001		<.0001	0.0062	0.0158	0.0009
3	0.7974	<.0001		<.0001	<.0001	<.0001
4	<.0001	0.0062	<.0001		<.0001	<.0001
5	<.0001	0.0158	<.0001	<.0001		0.2425
6	<.0001	0.0009	<.0001	<.0001	0.2425	
7	<.0001	0.6129	<.0001	0.0201	0.0048	0.0002
8	0.1388	<.0001	0.2157	<.0001	<.0001	<.0001
9	0.0254	<.0001	0.0442	0.0005	<.0001	<.0001
10	0.8075	<.0001	0.9895	<.0001	<.0001	<.0001
11	0.0939	<.0001	0.1507	<.0001	<.0001	<.0001

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Split28

i/j	7	8	9	10	11	12
1	<.0001	0.1388	0.0254	0.8075	0.0939	0.5203
2	0.6129	<.0001	<.0001	<.0001	<.0001	<.0001
3	<.0001	0.2157	0.0442	0.9895	0.1507	0.3708
4	0.0201	<.0001	0.0005	<.0001	<.0001	<.0001
5	0.0048	<.0001	<.0001	<.0001	<.0001	<.0001
6	0.0002	<.0001	<.0001	<.0001	<.0001	<.0001
7		<.0001	<.0001	<.0001	<.0001	<.0001
8	<.0001		0.4026	0.2111	0.8331	0.0390
9	<.0001	0.4026		0.0430	0.5288	0.0057
10	<.0001	0.2111	0.0430		0.1472	0.3777
11	<.0001	0.8331	0.5288	0.1472		0.0247

Table A4.21. One-Way ANOVA Analysis Data Sheet 21.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Split28

i/j	1	2	3	4	5	6
12	0.5203	<.0001	0.3708	<.0001	<.0001	<.0001

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Split28

i/j	7	8	9	10	11	12
12	<.0001	0.0390	0.0057	0.3777	0.0247	

TRT	E28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	237535.667	4574.678	<.0001	1
B	218183.667	4574.678	<.0001	2
C	220035.333	4574.678	<.0001	3
D	189350.000	4574.678	<.0001	4
E	173040.000	4574.678	<.0001	5
F	215425.667	4574.678	<.0001	6
G	149196.333	4574.678	<.0001	7
H	206787.333	4574.678	<.0001	8
I	161341.000	4574.678	<.0001	9
J	189661.667	4574.678	<.0001	10
K	169598.000	4574.678	<.0001	11
L	170883.333	4574.678	<.0001	12

Table A4.22. One-Way ANOVA Analysis Data Sheet 22.

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The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: E28

i/j	1	2	3	4	5	6
1		0.0063	0.0124	<.0001	<.0001	0.0023
2	0.0063		0.7772	0.0002	<.0001	0.6737
3	0.0124	0.7772		<.0001	<.0001	0.4830
4	<.0001	0.0002	<.0001		0.0188	0.0005
5	<.0001	<.0001	<.0001	0.0188		<.0001
6	0.0023	0.6737	0.4830	0.0005	<.0001	
7	<.0001	<.0001	<.0001	<.0001	0.0012	<.0001
8	<.0001	0.0909	0.0517	0.0126	<.0001	0.1943
9	<.0001	<.0001	<.0001	0.0002	0.0831	<.0001
10	<.0001	0.0002	<.0001	0.9620	0.0168	0.0006
11	<.0001	<.0001	<.0001	0.0055	0.5996	<.0001
12	<.0001	<.0001	<.0001	0.0087	0.7418	<.0001

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: E28

i/j	7	8	9	10	11	12
1	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
2	<.0001	0.0909	<.0001	0.0002	<.0001	<.0001
3	<.0001	0.0517	<.0001	<.0001	<.0001	<.0001
4	<.0001	0.0126	0.0002	0.9620	0.0055	0.0087
5	0.0012	<.0001	0.0831	0.0168	0.5996	0.7418
6	<.0001	0.1943	<.0001	0.0006	<.0001	<.0001
7		<.0001	0.0727	<.0001	0.0043	0.0027
8	<.0001		<.0001	0.0141	<.0001	<.0001
9	0.0727	<.0001		0.0002	0.2141	0.1532
10	<.0001	0.0141	0.0002		0.0049	0.0078
11	0.0043	<.0001	0.2141	0.0049		0.8442
12	0.0027	<.0001	0.1532	0.0078	0.8442	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Table A4.23. Two-Way ANOVA Analysis Data Sheet 1.

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Obs	TRT	Hemp	CR	COMP3	COMP7	COMP28	MOR7	MOR28	SPLIT28	E28
1	A	0.50	10	93.1	139.7	174.1	2.3	2.8	1969	184628
2	A	0.50	10	103.7	146.9	175.2	2.0	3.0	2010	194071
3	A	0.50	10	98.3	143.2	174.5	2.2	3.0	1809	189351
4	B	0.50	20	88.7	125.9	166.3	2.2	2.8	1560	188083
5	B	0.50	20	90.4	126.4	167.4	2.0	2.7	1672	157998
6	B	0.50	20	89.4	126.0	166.8	2.1	2.7	1715	173039
7	C	0.50	30	85.4	115.3	182.4	2.2	2.7	1601	225042
8	C	0.50	30	81.5	112.6	173.0	2.3	3.0	1578	205810
9	C	0.50	30	83.4	113.8	177.8	2.2	2.3	1588	215425
10	D	0.75	10	101.5	112.6	207.9	2.3	3.3	1815	144338
11	D	0.75	10	102.0	131.4	194.1	2.7	3.0	1794	154054
12	D	0.75	10	101.6	138.6	201.1	2.8	3.0	1805	149197
13	E	0.75	20	90.4	119.8	171.3	2.2	2.4	2269	220998
14	E	0.75	20	90.9	124.2	170.2	2.3	3.0	2144	192577
15	E	0.75	20	80.4	122.1	170.9	2.3	2.3	2107	206787
16	F	0.75	30	77.6	124.2	169.7	2.4	2.8	2163	163266
17	F	0.75	30	74.3	109.2	189.6	2.3	2.2	2062	159417
18	F	0.75	30	76.0	122.5	177.4	2.4	2.4	2167	161340
19	G	1.00	10	84.8	133.6	191.8	2.6	2.1	2246	189997
20	G	1.00	10	93.7	123.6	185.7	2.2	2.3	2230	189327
21	G	1.00	10	94.3	122.0	188.7	2.0	2.2	2237	189661
22	H	1.00	20	94.8	127.5	164.7	2.4	2.8	2131	175178
23	H	1.00	20	93.7	138.1	179.6	2.3	2.9	2195	164017
24	H	1.00	20	94.4	136.4	200.2	2.4	2.8	2162	169599
25	I	1.00	30	98.7	135.8	166.9	2.9	3.1	2298	162686
26	I	1.00	30	92.0	150.3	168.6	2.9	2.7	2268	179080
27	I	1.00	30	97.0	133.6	167.7	2.9	3.2	2282	170884

Table A4.24. Two-Way ANOVA Analysis Data Sheet 2.

--- TRT=A ---

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.5000000	0	0.5000000	0.5000000	0
CR	10.0000000	0	10.0000000	10.0000000	0
COMP3	98.3666667	5.3003145	93.1000000	103.7000000	3.0601380
COMP7	143.2666667	3.6004629	139.7000000	146.9000000	2.0787282
COMP28	174.6000000	0.5567764	174.1000000	175.2000000	0.3214550
MOR7	2.1666667	0.1527525	2.0000000	2.3000000	0.0881917
MOR28	2.9333333	0.1154701	2.8000000	3.0000000	0.0666667
SPLIT28	1929.33	106.2089136	1809.00	2010.00	61.3197449
E28	189350.00	4721.50	184628.00	194071.00	2725.96

--- TRT=B ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.5000000	0	0.5000000	0.5000000	0
CR	20.0000000	0	20.0000000	20.0000000	0
COMP3	89.5000000	0.8544004	88.7000000	90.4000000	0.4932883
COMP7	126.1000000	0.2645751	125.9000000	126.4000000	0.1527525
COMP28	166.8333333	0.5507571	166.3000000	167.4000000	0.3179797
MOR7	2.1000000	0.1000000	2.0000000	2.2000000	0.0577350
MOR28	2.7333333	0.0577350	2.7000000	2.8000000	0.0333333
SPLIT28	1649.00	80.0187478	1560.00	1715.00	46.1988456
E28	173040.00	15042.50	157998.00	188083.00	8684.79

--- TRT=C ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.5000000	0	0.5000000	0.5000000	0
CR	30.0000000	0	30.0000000	30.0000000	0
COMP3	83.4333333	1.9502137	81.5000000	85.4000000	1.1259564
COMP7	113.9000000	1.3527749	112.6000000	115.3000000	0.7810250
COMP28	177.7333333	4.7003546	173.0000000	182.4000000	2.7137510
MOR7	2.2333333	0.0577350	2.2000000	2.3000000	0.0333333
MOR28	2.6666667	0.3511885	2.3000000	3.0000000	0.2027588
SPLIT28	1589.00	11.5325626	1578.00	1601.00	6.6583281
E28	215425.67	9616.00	205810.00	225042.00	5551.80

Table A4.25. Two-Way ANOVA Analysis Data Sheet 3.

TRT=D

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.7500000	0	0.7500000	0.7500000	0
CR	10.0000000	0	10.0000000	10.0000000	0
COMP3	101.7000000	0.2645751	101.5000000	102.0000000	0.1527525
COMP7	127.5333333	13.4243560	112.6000000	138.6000000	7.7505555
COMP28	201.0333333	6.9002415	194.1000000	207.9000000	3.9838563
MOR7	2.6000000	0.2645751	2.3000000	2.8000000	0.1527525
MOR28	3.1000000	0.1732051	3.0000000	3.3000000	0.1000000
SPLIT28	1804.67	10.5039675	1794.00	1815.00	6.0644685
E28	149196.33	4858.00	144338.00	154054.00	2804.77

TRT=E

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.7500000	0	0.7500000	0.7500000	0
CR	20.0000000	0	20.0000000	20.0000000	0
COMP3	87.2333333	5.9231185	80.4000000	90.9000000	3.4197141
COMP7	122.0333333	2.2007574	119.8000000	124.2000000	1.2706079
COMP28	170.8000000	0.5567764	170.2000000	171.3000000	0.3214550
MOR7	2.2666667	0.0577350	2.2000000	2.3000000	0.0333333
MOR28	2.5666667	0.3785939	2.3000000	3.0000000	0.2185813
SPLIT28	2173.33	84.8901251	2107.00	2269.00	49.0113366
E28	206787.33	14210.50	192577.00	220998.00	8204.44

TRT=F

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	0.7500000	0	0.7500000	0.7500000	0
CR	30.0000000	0	30.0000000	30.0000000	0
COMP3	75.9666667	1.6502525	74.3000000	77.6000000	0.9527737
COMP7	118.6333333	8.2136066	109.2000000	124.2000000	4.7421280
COMP28	178.9000000	10.0344407	169.7000000	189.6000000	5.7933870
MOR7	2.3666667	0.0577350	2.3000000	2.4000000	0.0333333
MOR28	2.4666667	0.3055050	2.2000000	2.8000000	0.1763834
SPLIT28	2130.67	59.5007003	2062.00	2167.00	34.3527453
E28	161341.00	1924.50	159417.00	163266.00	1111.11

Table A4.26. Two-Way ANOVA Analysis Data Sheet 4.

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--- TRT=G ---

The MEANS Procedure

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	1.0000000	0	1.0000000	1.0000000	0
CR	10.0000000	0	10.0000000	10.0000000	0
COMP3	90.9333333	5.3200877	84.8000000	94.3000000	3.0715541
COMP7	126.4000000	6.2864935	122.0000000	133.6000000	3.6295087
COMP28	188.7333333	3.0501366	185.7000000	191.8000000	1.7609972
MOR7	2.2666667	0.3055050	2.0000000	2.6000000	0.1763834
MOR28	2.2000000	0.1000000	2.1000000	2.3000000	0.0577350
SPLIT28	2237.67	8.0208063	2230.00	2246.00	4.6308147
E28	189661.67	335.0004975	189327.00	189997.00	193.4126274

--- TRT=H ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	1.0000000	0	1.0000000	1.0000000	0
CR	20.0000000	0	20.0000000	20.0000000	0
COMP3	94.3000000	0.5567764	93.7000000	94.8000000	0.3214550
COMP7	134.0000000	5.6929781	127.5000000	138.1000000	3.2868425
COMP28	181.5000000	17.8261045	164.7000000	200.2000000	10.2919062
MOR7	2.3666667	0.0577350	2.3000000	2.4000000	0.0333333
MOR28	2.8333333	0.0577350	2.8000000	2.9000000	0.0333333
SPLIT28	2162.67	32.0052079	2131.00	2195.00	18.4782154
E28	169598.00	5580.50	164017.00	175178.00	3221.90

--- TRT=I ---

Variable	Mean	Std Dev	Minimum	Maximum	Std Error
Hemp	1.0000000	0	1.0000000	1.0000000	0
CR	30.0000000	0	30.0000000	30.0000000	0
COMP3	95.9000000	3.4828150	92.0000000	98.7000000	2.0108042
COMP7	139.9000000	9.0735880	133.6000000	150.3000000	5.2386385
COMP28	167.7333333	0.8504901	166.9000000	168.6000000	0.4910307
MOR7	2.9000000	0	2.9000000	2.9000000	0
MOR28	3.0000000	0.2645751	2.7000000	3.2000000	0.1527525
SPLIT28	2282.67	15.0111070	2268.00	2298.00	8.6666667
E28	170883.33	8197.00	162686.00	179080.00	4732.54

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The GLM Procedure

Class Level Information

Class	Levels	Values
TRT	9	A B C D E F G H I

Number of Observations Read	27
Number of Observations Used	27

Table A4.27. Two-Way ANOVA Analysis Data Sheet 5.

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The GLM Procedure

Dependent Variable: COMP3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1509.140741	188.642593	15.26	<.0001
Error	18	222.493333	12.360741		
Corrected Total	26	1731.634074			

R-Square	Coeff Var	Root MSE	COMP3 Mean
0.871512	3.871378	3.515785	90.81481

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	1509.140741	188.642593	15.26	<.0001

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The GLM Procedure

Dependent Variable: COMP7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	2217.625185	277.203148	5.92	0.0009
Error	18	843.286667	46.849259		
Corrected Total	26	3060.911852			

R-Square	Coeff Var	Root MSE	COMP7 Mean
0.724498	5.348468	6.844652	127.9741

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	2217.625185	277.203148	5.92	0.0009

Table A4.28. Two-Way ANOVA Analysis Data Sheet 6.

The GLM Procedure

Dependent Variable: COMP28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	2845.634074	355.704259	6.41	0.0005
Error	18	998.233333	55.457407		
Corrected Total	26	3843.867407			

R-Square	Coeff Var	Root MSE	COMP28 Mean
0.740305	4.168428	7.446973	178.6519

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	2845.634074	355.704259	6.41	0.0005

The GLM Procedure

Dependent Variable: MOR7

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1.46296296	0.18287037	7.84	0.0002
Error	18	0.42000000	0.02333333		
Corrected Total	26	1.88296296			

R-Square	Coeff Var	Root MSE	MOR7 Mean
0.776947	6.464448	0.152753	2.362963

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	1.46296296	0.18287037	7.84	0.0002

Table A4.29. Two-Way ANOVA Analysis Data Sheet 7.

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The GLM Procedure

Dependent Variable: MOR28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1.92666667	0.24083333	4.42	0.0042
Error	18	0.98000000	0.05444444		
Corrected Total	26	2.90666667			

R-Square	Coeff Var	Root MSE	MOR28 Mean
0.662844	8.571429	0.233333	2.722222

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	1.92666667	0.24083333	4.42	0.0042

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The GLM Procedure

Dependent Variable: SPLIT28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1635146.000	204393.250	61.34	<.0001
Error	18	59974.667	3331.926		
Corrected Total	26	1695120.667			

R-Square	Coeff Var	Root MSE	SPLIT28 Mean
0.964619	2.892731	57.72284	1995.444

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	1635146.000	204393.250	61.34	<.0001

Table A4.30. Two-Way ANOVA Analysis Data Sheet 8.

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The GLM Procedure

Dependent Variable: E28

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	11060966558	1382620820	18.61	<.0001
Error	18	1337448035	74302669		
Corrected Total	26	12398414593			

R-Square	Coeff Var	Root MSE	E28 Mean
0.892127	4.773266	8619.900	180587.0

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRT	8	11060966558	1382620820	18.61	<.0001

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The GLM Procedure

Duncan's Multiple Range Test for COMP3

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	12.36074

Number of Means	2	3	4	5	6	7	8	9
Critical Range	6.031	6.328	6.515	6.645	6.740	6.811	6.867	6.910

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	TRT
	A		101.700	3	D
	A				
B	A		98.367	3	A
B	A				
B	A	C	95.900	3	I
B		C			
B		C	94.300	3	H
		C			
	D	C	90.933	3	G
	D	C			
E	D	C	89.500	3	B
E	D				
E	D		87.233	3	E
E					
E			83.433	3	C
	F		75.967	3	F

Table A4.31. Two-Way ANOVA Analysis Data Sheet 9.

```
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                       The GLM Procedure

              Duncan's Multiple Range Test for COMP7

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
                              rate.


                  Alpha                            0.05
                  Error Degrees of Freedom           18
                  Error Mean Square            46.84926


Number of Means          2          3          4          5          6          7          8          9
Critical Range       11.74      12.32      12.68      12.94      13.12      13.26      13.37      13.45


            Means with the same letter are not significantly different.


              Duncan Grouping          Mean       N    TRT

                       A            143.267      3    A
                       A
                       A            139.900      3    I
                       A
                  B    A            134.000      3    H
                  B
                  B    C            127.533      3    D
                  B    C
                  B    C    D       126.400      3    G
                  B    C    D
                  B    C    D       126.100      3    B
                  B    C    D
                  B    C    D       122.033      3    E
                       C    D
                       C    D       118.633      3    F
                            D
                            D       113.900      3    C
```

Table A4.32. Two-Way ANOVA Analysis Data Sheet 10.

The GLM Procedure

Duncan's Multiple Range Test for COMP28

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	55.45741

Number of Means	2	3	4	5	6	7	8	9
Critical Range	12.77	13.40	13.80	14.07	14.28	14.43	14.54	14.64

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	TRT
	A		201.033	3	D
	A				
B	A		188.733	3	G
B					
B	C		181.500	3	H
B	C				
B	C	D	178.900	3	F
B	C	D			
B	C	D	177.733	3	C
	C	D			
	C	D	174.600	3	A
	C	D			
	C	D	170.800	3	E
	C	D			
	C	D	167.733	3	I
		D			
		D	166.833	3	B

Table A4.33. Two-Way ANOVA Analysis Data Sheet 11.

The GLM Procedure

Duncan's Multiple Range Test for MOR7

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.023333

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.2620	.2749	.2831	.2887	.2928	.2959	.2983	.3002

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TRT
	A	2.9000	3	I
	B	2.6000	3	D
	B			
C	B	2.3667	3	F
C	B			
C	B	2.3667	3	H
C				
C		2.2667	3	G
C				
C		2.2667	3	E
C				
C		2.2333	3	C
C				
C		2.1667	3	A
C				
C		2.1000	3	B

Table A4.34. Two-Way ANOVA Analysis Data Sheet 12.

The GLM Procedure

Duncan's Multiple Range Test for MOR28

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.054444

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.4003	.4200	.4324	.4410	.4473	.4521	.4557	.4586

Means with the same letter are not significantly different.

```
Duncan Grouping          Mean      N    TRT

          A            3.1000      3    D
          A
     B    A            3.0000      3    I
     B    A
     B    A            2.9333      3    A
     B    A
     B    A    C       2.8333      3    H
     B    A    C
     B    A    C       2.7333      3    B
     B    A    C
     B    A    C       2.6667      3    C
     B         C
     B    D    C       2.5667      3    E
          D    C
          D    C       2.4667      3    F
          D
          D            2.2000      3    G
```

Table A4.35. Two-Way ANOVA Analysis Data Sheet 13.

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The GLM Procedure

Duncan's Multiple Range Test for SPLIT28

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	3331.926

Number of Means	2	3	4	5	6	7	8	9
Critical Range	99.0	103.9	107.0	109.1	110.7	111.8	112.7	113.5

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TRT
	A	2282.67	3	I
	A			
B	A	2237.67	3	G
B				
B	C	2173.33	3	E
B	C			
B	C	2162.67	3	H
	C			
	C	2130.67	3	F
	D	1929.33	3	A
	E	1804.67	3	D
	F	1649.00	3	B
	F			
	F	1589.00	3	C

Table A4.36. Two-Way ANOVA Analysis Data Sheet 14.

The GLM Procedure

Duncan's Multiple Range Test for E28

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	74302669

Number of Means	2	3	4	5	6	7	8	9
Critical Range	14787	15514	15974	16292	16524	16700	16836	16942

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TRT
	A	215426	3	C
	A			
	A	206787	3	E
	B	189662	3	G
	B			
	B	189350	3	A
	C	173040	3	B
	C			
	C	170883	3	I
	C			
	C	169598	3	H
	C			
D	C	161341	3	F
D				
D		149196	3	D

Table A4.37. Two-Way ANOVA Analysis Data Sheet 15.

The GLM Procedure
Least Squares Means

TRT	COMP3 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	98.366667	2.029839	<.0001	1
B	89.500000	2.029839	<.0001	2
C	83.433333	2.029839	<.0001	3
D	101.700000	2.029839	<.0001	4
E	87.233333	2.029839	<.0001	5
F	75.966667	2.029839	<.0001	6
G	90.933333	2.029839	<.0001	7
H	94.300000	2.029839	<.0001	8
I	95.900000	2.029839	<.0001	9

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP3

i/j	1	2	3	4	5	6	7	8	9
1		0.0063	<.0001	0.2607	0.0011	<.0001	0.0185	0.1737	0.4015
2	0.0063		0.0488	0.0005	0.4400	0.0002	0.6236	0.1118	0.0388
3	<.0001	0.0488		<.0001	0.2022	0.0181	0.0176	0.0014	0.0004
4	0.2607	0.0005	<.0001		<.0001	<.0001	0.0015	0.0190	0.0585
5	0.0011	0.4400	0.2022	<.0001		0.0010	0.2137	0.0242	0.0074
6	<.0001	0.0002	0.0181	<.0001	0.0010		<.0001	<.0001	<.0001
7	0.0185	0.6236	0.0176	0.0015	0.2137	<.0001		0.2562	0.1007
8	0.1737	0.1118	0.0014	0.0190	0.0242	<.0001	0.2562		0.5841
9	0.4015	0.0388	0.0004	0.0585	0.0074	<.0001	0.1007	0.5841	

TRT	COMP7 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	143.266667	3.951762	<.0001	1
B	126.100000	3.951762	<.0001	2
C	113.900000	3.951762	<.0001	3
D	127.533333	3.951762	<.0001	4
E	122.033333	3.951762	<.0001	5
F	118.633333	3.951762	<.0001	6
G	126.400000	3.951762	<.0001	7
H	134.000000	3.951762	<.0001	8
I	139.900000	3.951762	<.0001	9

Table A4.38. Two-Way ANOVA Analysis Data Sheet 16.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP7

i/j	1	2	3	4	5	6	7	8	9
1		0.0066	<.0001	0.0115	0.0013	0.0003	0.0074	0.1146	0.5544
2	0.0066		0.0425	0.8005	0.4762	0.1982	0.9578	0.1745	0.0238
3	<.0001	0.0425		0.0253	0.1628	0.4081	0.0382	0.0021	0.0002
4	0.0115	0.8005	0.0253		0.3381	0.1287	0.8416	0.2624	0.0401
5	0.0013	0.4762	0.1628	0.3381		0.5505	0.4448	0.0462	0.0050
6	0.0003	0.1982	0.4081	0.1287	0.5505		0.1816	0.0132	0.0013
7	0.0074	0.9578	0.0382	0.8416	0.4448	0.1816		0.1907	0.0266
8	0.1146	0.1745	0.0021	0.2624	0.0462	0.0132	0.1907		0.3051
9	0.5544	0.0238	0.0002	0.0401	0.0050	0.0013	0.0266	0.3051	

TRT	COMP28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	174.600000	4.299512	<.0001	1
B	166.833333	4.299512	<.0001	2
C	177.733333	4.299512	<.0001	3
D	201.033333	4.299512	<.0001	4
E	170.800000	4.299512	<.0001	5
F	178.900000	4.299512	<.0001	6
G	188.733333	4.299512	<.0001	7
H	181.500000	4.299512	<.0001	8
I	167.733333	4.299512	<.0001	9

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: COMP28

i/j	1	2	3	4	5	6	7	8	9
1		0.2177	0.6126	0.0004	0.5398	0.4885	0.0320	0.2714	0.2736
2	0.2177		0.0899	<.0001	0.5224	0.0627	0.0020	0.0268	0.8840
3	0.6126	0.0899		0.0012	0.2691	0.8500	0.0872	0.5434	0.1174
4	0.0004	<.0001	0.0012		<.0001	0.0019	0.0582	0.0048	<.0001
5	0.5398	0.5224	0.2691	<.0001		0.1994	0.0086	0.0954	0.6201
6	0.4885	0.0627	0.8500	0.0019	0.1994		0.1232	0.6740	0.0829
7	0.0320	0.0020	0.0872	0.0582	0.0086	0.1232		0.2497	0.0028
8	0.2714	0.0268	0.5434	0.0048	0.0954	0.6740	0.2497		0.0362
9	0.2736	0.8840	0.1174	<.0001	0.6201	0.0829	0.0028	0.0362	

Table A4.39. Two-Way ANOVA Analysis Data Sheet 17.

The GLM Procedure
Least Squares Means

TRT	MOR7 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	2.16666667	0.08819171	<.0001	1
B	2.10000000	0.08819171	<.0001	2
C	2.23333333	0.08819171	<.0001	3
D	2.60000000	0.08819171	<.0001	4
E	2.26666667	0.08819171	<.0001	5
F	2.36666667	0.08819171	<.0001	6
G	2.26666667	0.08819171	<.0001	7
H	2.36666667	0.08819171	<.0001	8
I	2.90000000	0.08819171	<.0001	9

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR7

i/j	1	2	3	4	5	6	7	8	9
1		0.5995	0.5995	0.0027	0.4331	0.1262	0.4331	0.1262	<.0001
2	0.5995		0.2992	0.0008	0.1981	0.0465	0.1981	0.0465	<.0001
3	0.5995	0.2992		0.0088	0.7923	0.2992	0.7923	0.2992	<.0001
4	0.0027	0.0008	0.0088		0.0155	0.0777	0.0155	0.0777	0.0271
5	0.4331	0.1981	0.7923	0.0155		0.4331	1.0000	0.4331	<.0001
6	0.1262	0.0465	0.2992	0.0777	0.4331		0.4331	1.0000	0.0005
7	0.4331	0.1981	0.7923	0.0155	1.0000	0.4331		0.4331	<.0001
8	0.1262	0.0465	0.2992	0.0777	0.4331	1.0000	0.4331		0.0005
9	<.0001	<.0001	<.0001	0.0271	<.0001	0.0005	<.0001	0.0005	

TRT	MOR28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	2.93333333	0.13471506	<.0001	1
B	2.73333333	0.13471506	<.0001	2
C	2.66666667	0.13471506	<.0001	3
D	3.10000000	0.13471506	<.0001	4
E	2.56666667	0.13471506	<.0001	5
F	2.46666667	0.13471506	<.0001	6
G	2.20000000	0.13471506	<.0001	7
H	2.83333333	0.13471506	<.0001	8
I	3.00000000	0.13471506	<.0001	9

Table A4.40. Two-Way ANOVA Analysis Data Sheet 18.

The GLM Procedure
Least Squares Means

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: MOR28

i/j	1	2	3	4	5	6	7	8	9
1		0.3077	0.1786	0.3932	0.0702	0.0248	0.0012	0.6061	0.7305
2	0.3077		0.7305	0.0702	0.3932	0.1786	0.0119	0.6061	0.1786
3	0.1786	0.7305		0.0354	0.6061	0.3077	0.0248	0.3932	0.0972
4	0.3932	0.0702	0.0354		0.0119	0.0038	0.0002	0.1786	0.6061
5	0.0702	0.3932	0.6061	0.0119		0.6061	0.0702	0.1786	0.0354
6	0.0248	0.1786	0.3077	0.0038	0.6061		0.1786	0.0702	0.0119
7	0.0012	0.0119	0.0248	0.0002	0.0702	0.1786		0.0038	0.0005
8	0.6061	0.6061	0.3932	0.1786	0.1786	0.0702	0.0038		0.3932
9	0.7305	0.1786	0.0972	0.6061	0.0354	0.0119	0.0005	0.3932	

TRT	SPLIT28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	1929.33333	33.32630	<.0001	1
B	1649.00000	33.32630	<.0001	2
C	1589.00000	33.32630	<.0001	3
D	1804.66667	33.32630	<.0001	4
E	2173.33333	33.32630	<.0001	5
F	2130.66667	33.32630	<.0001	6
G	2237.66667	33.32630	<.0001	7
H	2162.66667	33.32630	<.0001	8
I	2282.66667	33.32630	<.0001	9

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: SPLIT28

i/j	1	2	3	4	5	6	7	8	9
1		<.0001	<.0001	0.0165	<.0001	0.0005	<.0001	0.0001	<.0001
2	<.0001		0.2192	0.0040	<.0001	<.0001	<.0001	<.0001	<.0001
3	<.0001	0.2192		0.0002	<.0001	<.0001	<.0001	<.0001	<.0001
4	0.0165	0.0040	0.0002		<.0001	<.0001	<.0001	<.0001	<.0001
5	<.0001	<.0001	<.0001	<.0001		0.3773	0.1891	0.8235	0.0323
6	0.0005	<.0001	<.0001	<.0001	0.3773		0.0357	0.5058	0.0047
7	<.0001	<.0001	<.0001	<.0001	0.1891	0.0357		0.1289	0.3523
8	0.0001	<.0001	<.0001	<.0001	0.8235	0.5058	0.1289		0.0203
9	<.0001	<.0001	<.0001	<.0001	0.0323	0.0047	0.3523	0.0203	

Table A4.41. Two-Way ANOVA Analysis Data Sheet 19.

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The GLM Procedure
Least Squares Means

TRT	E28 LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
A	189350.000	4976.701	<.0001	1
B	173040.000	4976.701	<.0001	2
C	215425.667	4976.701	<.0001	3
D	149196.333	4976.701	<.0001	4
E	206787.333	4976.701	<.0001	5
F	161341.000	4976.701	<.0001	6
G	189661.667	4976.701	<.0001	7
H	169598.000	4976.701	<.0001	8
I	170883.333	4976.701	<.0001	9

Least Squares Means for effect TRT
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: E28

i/j	1	2	3	4	5	6	7	8	9
1		0.0325	0.0016	<.0001	0.0234	0.0009	0.9652	0.0117	0.0172
2	0.0325		<.0001	0.0033	0.0001	0.1138	0.0297	0.6307	0.7628
3	0.0016	<.0001		<.0001	0.2355	<.0001	0.0018	<.0001	<.0001
4	<.0001	0.0033	<.0001		<.0001	0.1016	<.0001	0.0096	0.0064
5	0.0234	0.0001	0.2355	<.0001		<.0001	0.0256	<.0001	<.0001
6	0.0009	0.1138	<.0001	0.1016	<.0001		0.0008	0.2560	0.1919
7	0.9652	0.0297	0.0018	<.0001	0.0256	0.0008		0.0106	0.0157
8	0.0117	0.6307	<.0001	0.0096	<.0001	0.2560	0.0106		0.8571
9	0.0172	0.7628	<.0001	0.0064	<.0001	0.1919	0.0157	0.8571	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

APPENDIX 5

PHASE ONE ANALYTICAL MODEL DATA TABLES

Table A5.1. Data for the Compressive Strength Linear Model with V_f Only.

Mix	V_f (%)	CR (%)	Comp. Meas. (MPa)	Comp. Pred. (MPa)	E^2
0.5% Hemp - 10% coarse	0.5	NA	17.5	17.6	0.008
0.5% Hemp - 20% coarse	0.5	NA	16.7	17.6	0.746
0.5% Hemp - 30% coarse	0.5	NA	17.8	17.6	0.047
0.75% Hemp - 10% coarse	0.75	NA	20.1	17.9	4.962
0.75% Hemp - 20% coarse	0.75	NA	17.1	17.9	0.631
0.75% Hemp - 30% coarse	0.75	NA	17.9	17.9	0.000
1% Hemp - 10% coarse	1.0	NA	18.9	18.2	0.475
1% Hemp - 20% coarse	1.0	NA	18.2	18.2	0.000
1% Hemp - 30% coarse	1.0	NA	16.8	18.2	2.010
					8.879

Table A5.2. Data for the Compressive Strength Linear Model with V_f and AR.

Mix	V_f (%)	CR (%)	Comp. Meas. (MPa)	Comp. Pred. (MPa)	E^2
0.5% Hemp - 10% coarse	0.5	NA	17.5	17.5	0.007
0.5% Hemp - 20% coarse	0.5	NA	16.7	17.5	0.742
0.5% Hemp - 30% coarse	0.5	NA	17.8	17.5	0.048
0.75% Hemp - 10% coarse	0.75	NA	20.1	17.9	4.962
0.75% Hemp - 20% coarse	0.75	NA	17.1	17.9	0.631
0.75% Hemp - 30% coarse	0.75	NA	17.9	17.9	0.000
1% Hemp - 10% coarse	1.0	NA	18.9	18.2	0.471
1% Hemp - 20% coarse	1.0	NA	18.2	18.2	0.000
1% Hemp - 30% coarse	1.0	NA	16.8	18.2	2.017
					8.879

Table A5.3. Data for the Compressive Strength Linear Model with CR Only.

Mix	V_f (%)	CR (%)	Comp. Meas. (MPa)	Comp. Pred. (MPa)	E^2
0.5% Hemp - 10% coarse	NA	10	17.5	18.5	1.155
0.5% Hemp - 20% coarse	NA	20	16.7	17.9	1.398
0.5% Hemp - 30% coarse	NA	30	17.8	17.2	0.322
0.75% Hemp - 10% coarse	NA	10	20.1	18.5	2.431
0.75% Hemp - 20% coarse	NA	20	17.1	17.9	0.631
0.75% Hemp - 30% coarse	NA	30	17.9	17.2	0.473
1% Hemp - 10% coarse	NA	10	18.9	18.5	0.115
1% Hemp - 20% coarse	NA	20	18.2	17.9	0.108
1% Hemp - 30% coarse	NA	30	16.8	17.2	0.186
					6.817

Table A5.4. Data for the Compressive Strength Linear Model with CR and V_f.

Mix	V_f (%)	CR (%)	Comp. Meas. (MPa)	Comp. Pred. (MPa)	E^2
0.5% Hemp - 10% coarse	0.5	10	17.5	18.5	1.170
0.5% Hemp - 20% coarse	0.5	20	16.7	17.9	1.430
0.5% Hemp - 30% coarse	0.5	30	17.8	17.2	0.300
0.75% Hemp - 10% coarse	0.75	10	20.1	18.5	2.455
0.75% Hemp - 20% coarse	0.75	20	17.1	17.9	0.631
0.75% Hemp - 30% coarse	0.75	30	17.9	17.2	0.462
1% Hemp - 10% coarse	1.0	10	18.9	18.5	0.131
1% Hemp - 20% coarse	1.0	20	18.2	17.9	0.117
1% Hemp - 30% coarse	1.0	30	16.8	17.2	0.182
					6.878

Table A5.5. Data for the Compressive Strength Linear Model with CR , V_f, and AR.

Mix	V_f (%)	CR (%)	Comp. Meas. (MPa)	Comp. Pred. (MPa)	E^2
0.5% Hemp - 10% coarse	0.5	10	17.5	18.2	0.569
0.5% Hemp - 20% coarse	0.5	20	16.7	17.5	0.742
0.5% Hemp - 30% coarse	0.5	30	17.8	16.9	0.791
0.75% Hemp - 10% coarse	0.75	10	20.1	18.5	2.434
0.75% Hemp - 20% coarse	0.75	20	17.1	17.9	0.631
0.75% Hemp - 30% coarse	0.75	30	17.9	17.2	0.471
1% Hemp - 10% coarse	1.0	10	18.9	18.9	0.000
1% Hemp - 20% coarse	1.0	20	18.2	18.2	0.000
1% Hemp - 30% coarse	1.0	30	16.8	17.5	0.569
					6.206

Table A5.6. Data for the Modulus Linear Model with V_f Only.

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	0.5	NA	18,935	18,107.8	0.684
0.5% Hemp - 20% coarse	0.5	NA	17,304	18,107.8	0.646
0.5% Hemp - 30% coarse	0.5	NA	21,543	18,107.8	11.798
0.75% Hemp - 10% coarse	0.75	NA	14,920	18,059.9	9.862
0.75% Hemp - 20% coarse	0.75	NA	20,679	18,059.9	6.858
0.75% Hemp - 30% coarse	0.75	NA	16,134	18,059.9	3.709
1% Hemp - 10% coarse	1.0	NA	18,966	18,012.1	0.910
1% Hemp - 20% coarse	1.0	NA	16,960	18,012.1	1.107
1% Hemp - 30% coarse	1.0	NA	17,088	18,012.1	0.853
					36.428

Table A5.7. Data for the Modulus Linear Model with V_f and AR.

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	0.5	NA	18,935	11,506.9	55.176
0.5% Hemp - 20% coarse	0.5	NA	17,304	11,506.9	33.607
0.5% Hemp - 30% coarse	0.5	NA	21,543	11,506.9	100.715
0.75% Hemp - 10% coarse	0.75	NA	14,920	16,723.0	3.252
0.75% Hemp - 20% coarse	0.75	NA	20,679	16,723.0	15.648
0.75% Hemp - 30% coarse	0.75	NA	16,134	16,723.0	0.347
1% Hemp - 10% coarse	1.0	NA	18,966	21,939.1	8.838
1% Hemp - 20% coarse	1.0	NA	16,960	21,939.1	24.794
1% Hemp - 30% coarse	1.0	NA	17,088	21,939.1	23.530
					265.906

Table A5.8. Data for the Modulus Linear Model with CR Only.

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	NA	10	18,935	17,734.8	1.441
0.5% Hemp - 20% coarse	NA	20	17,304	18,058.7	0.570
0.5% Hemp - 30% coarse	NA	30	21,543	18,382.6	9.985
0.75% Hemp - 10% coarse	NA	10	14,920	17,734.8	7.925
0.75% Hemp - 20% coarse	NA	20	20,679	18,058.7	6.865
0.75% Hemp - 30% coarse	NA	30	16,134	18,382.6	5.056
1% Hemp - 10% coarse	NA	10	18,966	17,734.8	1.517
1% Hemp - 20% coarse	NA	20	16,960	18,058.7	1.208
1% Hemp - 30% coarse	NA	30	17,088	18,382.6	1.675
					36.241

Table A5.9. Data for the Modulus Linear Model with CR and V_f.

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	0.5	10	18,935	17,742.0	1.423
0.5% Hemp - 20% coarse	0.5	20	17,304	18,052.5	0.560
0.5% Hemp - 30% coarse	0.5	30	21,543	18,362.9	10.110
0.75% Hemp - 10% coarse	0.75	10	14,920	17,749.0	8.006
0.75% Hemp - 20% coarse	0.75	20	20,679	18,058.7	6.865
0.75% Hemp - 30% coarse	0.75	30	16,134	18,368.4	4.992
1% Hemp - 10% coarse	1.0	10	18,966	17,756.0	1.465
1% Hemp - 20% coarse	1.0	20	16,960	18,064.9	1.221
1% Hemp - 30% coarse	1.0	30	17,088	18,373.8	1.653
					36.295

Table A5.10. Data for the Modulus Linear Model with CR , V_f, and AR.

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	0.5	10	18,935	18,526.6	0.167
0.5% Hemp - 20% coarse	0.5	20	17,304	18,853.2	2.400
0.5% Hemp - 30% coarse	0.5	30	21,543	19,179.9	5.582
0.75% Hemp - 10% coarse	0.75	10	14,920	17,732.8	7.914
0.75% Hemp - 20% coarse	0.75	20	20,679	18,058.7	6.865
0.75% Hemp - 30% coarse	0.75	30	16,134	18,384.6	5.064
1% Hemp - 10% coarse	1.0	10	18,966	16,939.1	4.109
1% Hemp - 20% coarse	1.0	20	16,960	17,264.2	0.093
1% Hemp - 30% coarse	1.0	30	17,088	17,589.2	0.251
					32.445

Table A5.11. Data for the Modulus Linear Model with CR , V_f, and AR (Two Outliers Removed).

Mix	V_f (%)	CR (%)	$E_{avg.meas.}$ (MPa)	$E_{pred.}$ (MPa)	$E^2(/10^6)$
0.5% Hemp - 10% coarse	0.5	10	18,935	19,194.2	0.067
0.5% Hemp - 20% coarse	0.5	20	17,304	18,024.0	0.518
0.5% Hemp - 30% coarse	0.5	30	21,543		
0.75% Hemp - 10% coarse	0.75	10	14,920		
0.75% Hemp - 20% coarse	0.75	20	20,679	18,010.9	7.118
0.75% Hemp - 30% coarse	0.75	30	16,134	16,843.6	0.503
1% Hemp - 10% coarse	1.0	10	18,966	19,162.2	0.038
1% Hemp - 20% coarse	1.0	20	16,960	17,997.8	1.078
1% Hemp - 30% coarse	1.0	30	17,088	16,833.5	0.065
					9.387

Table A5.12. Data for the Flexure Linear Model with V_f Only.

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	0.5	NA	21.88	20.5	8.867
0.5% Hemp - 20% coarse	0.5	NA	20.52	20.5	1.826
0.5% Hemp - 30% coarse	0.5	NA	19.96	20.5	0.000
0.75% Hemp - 10% coarse	0.75	NA	23.51	19.9	0.011
0.75% Hemp - 20% coarse	0.75	NA	19.38	19.9	13.370
0.75% Hemp - 30% coarse	0.75	NA	18.39	19.9	0.219
1% Hemp - 10% coarse	1.0	NA	16.39	19.2	0.617
1% Hemp - 20% coarse	1.0	NA	21.07	19.2	7.718
1% Hemp - 30% coarse	1.0	NA	22.51	19.2	3.600
					36.229

Table A5.13. Data for the Flexure Linear Model with V_f and AR.

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	0.5	NA	21.88	20.8	1.169
0.5% Hemp - 20% coarse	0.5	NA	20.52	20.8	0.075
0.5% Hemp - 30% coarse	0.5	NA	19.96	20.8	0.710
0.75% Hemp - 10% coarse	0.75	NA	23.51	20.4	9.647
0.75% Hemp - 20% coarse	0.75	NA	19.38	20.4	1.038
0.75% Hemp - 30% coarse	0.75	NA	18.39	20.4	4.059
1% Hemp - 10% coarse	1.0	NA	16.39	20.0	13.027
1% Hemp - 20% coarse	1.0	NA	21.07	20.0	1.137
1% Hemp - 30% coarse	1.0	NA	22.51	20.0	6.285
					37.148

Table A5.14. Data for the Flexure Linear Model with CR Only.

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	NA	10	21.88	20.6	1.754
0.5% Hemp - 20% coarse	NA	20	20.52	20.4	0.015
0.5% Hemp - 30% coarse	NA	30	19.96	20.2	0.084
0.75% Hemp - 10% coarse	NA	10	23.51	20.6	8.710
0.75% Hemp - 20% coarse	NA	20	19.38	20.4	1.038
0.75% Hemp - 30% coarse	NA	30	18.39	20.2	3.459
1% Hemp - 10% coarse	NA	10	16.39	20.6	17.320
1% Hemp - 20% coarse	NA	20	21.07	20.4	0.447
1% Hemp - 30% coarse	NA	30	22.51	20.2	5.126
					37.954

Table A5.15. Data for the Flexure Linear Model with CR and V_f.

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	0.5	10	21.88	20.6	1.714
0.5% Hemp - 20% coarse	0.5	20	20.52	20.4	0.014
0.5% Hemp - 30% coarse	0.5	30	19.96	20.2	0.079
0.75% Hemp - 10% coarse	0.75	10	23.51	20.6	8.643
0.75% Hemp - 20% coarse	0.75	20	19.38	20.4	1.038
0.75% Hemp - 30% coarse	0.75	30	18.39	20.2	3.417
1% Hemp - 10% coarse	1.0	10	16.39	20.6	17.383
1% Hemp - 20% coarse	1.0	20	21.07	20.4	0.451
1% Hemp - 30% coarse	1.0	30	22.51	20.2	5.191
					37.932

Table A5.16. Data for the Flexure Linear Model with CR, V_f, and AR.

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	0.5	10	21.88	21.0	0.852
0.5% Hemp - 20% coarse	0.5	20	20.52	20.8	0.075
0.5% Hemp - 30% coarse	0.5	30	19.96	20.6	0.468
0.75% Hemp - 10% coarse	0.75	10	23.51	20.6	8.690
0.75% Hemp - 20% coarse	0.75	20	19.38	20.4	1.038
0.75% Hemp - 30% coarse	0.75	30	18.39	20.2	3.447
1% Hemp - 10% coarse	1.0	10	16.39	20.2	14.190
1% Hemp - 20% coarse	1.0	20	21.07	20.0	1.137
1% Hemp - 30% coarse	1.0	30	22.51	19.8	7.101
					36.998

Table A5.17. Data for the Flexure Linear Model with CR, V_f, and AR (One Outlier Removed).

Mix	V_f (%)	CR (%)	$P_{max.meas.}$ (kN)	$P_{max.pred.}$ (kN)	E^2
0.5% Hemp - 10% coarse	0.5	10	21.88	21.7	0.029
0.5% Hemp - 20% coarse	0.5	20	20.52	20.4	0.010
0.5% Hemp - 30% coarse	0.5	30	19.96	19.1	0.673
0.75% Hemp - 10% coarse	0.75	10	23.51	22.4	1.145
0.75% Hemp - 20% coarse	0.75	20	19.38	21.2	3.137
0.75% Hemp - 30% coarse	0.75	30	18.39	19.9	2.200
1% Hemp - 10% coarse	1.0	10	16.39		
1% Hemp - 20% coarse	1.0	20	21.07	21.9	0.663
1% Hemp - 30% coarse	1.0	30	22.51	20.6	3.636
					11.494

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