A Study on Cork-based Plastic Composite Material

by

Sungmin Kim

S.M. Mechanical Engineering
Massachusetts Institute of Technology, 2009

B.S. Mechanical Engineering
Seoul National University, 2006

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Signature of Author ....

Department of Mechanical Engineering

August, 2011

Certified by..

David Wallace

Professor

Thesis Supervisor

Accepted by..

Dave E. Hardt

Chairman, Department Committee on Graduate Students

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Abstract
Sandwich panels are mainly used in construction for lightweight structures since their concept is appropriate due to extremely high in-plane and flexural stiffness to weight ratios. However, low structural freedom and high environmental burdens of core material in sandwich panels such as fiberglass, and chemically synthesized foams have retarded a wide use in various areas. Recently it has been suggested that the better performance and economic, environmental benefits could be possibly achieved by using hybrid sandwich panels comprising non-traditional pairs of materials for sandwich panels. Therefore, in this paper, a cork-based plastic composite material has been proposed as a new core material and the possibility for substituting existing core materials have been explored by investigation on its mechanical properties, economic benefit, and environmental impact. Several mechanical testing were carried out on the cork composite and Glass Fiber Reinforced Plastic (GFRP) to determine the mechanical properties and compare their relative performances. By conducting property-limited design cases with the obtained mechanical properties, how they will perform in light, stiff panel application was investigated. Economic analysis was demonstrated with a table top application by using rigidity equality condition. Finally, Eco-impact of the cork composite was investigated by conducting Life Cycle Assessment. The result proved that the cork composite is competitive with other core materials.

Thesis Supervisor: David Wallace
Professor of Mechanical Engineering

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Chapter 1 Introduction

1.1. Motivation

Sandwich structure consists of a low density core with stiff skins. It offers considerable potential for weight saving in panel applications such as car body panels, ships and aero vehicle constructions, where the main loads are flexural.[1] Therefore, sandwich construction becomes more acceptable in various fields where specifications demand high strength to weight ratio, faster construction, better thermal insulation and electromagnetic properties.[2] Since the structural properties of sandwich panels vary with core/facing materials, and the thickness of the sandwich panels, the concept of sandwich panel construction is to design their properties in such a way that the maximum stiffness and strength is achieved with minimum weight of facing and core material combinations. This optimization is important not only in terms of reducing the weight of sandwich structures, but is also economic as the costs are normally related to weight of materials used. The material for sandwich panels of interest for structural applications mainly include glass fiber reinforced plastics (GFRP)/carbon fiber-reinforced plastics (CFRP) skins with honeycomb or foam cores. [3]

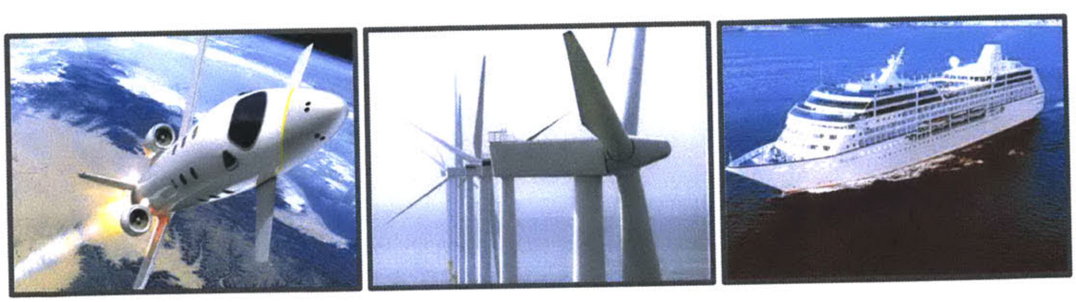


Figure 1-1: Sandwich panel applications in various areas

There are various core materials currently in use. Cellular foams, balsa wood, and metallic and non-metallic honeycombs are typical core materials. Cores are the weakest part of sandwich panels but maintain the distance between two facing laminates, provide compressive strength and withstand shear deformation of the structures.[1] The flexural stiffness of sandwich panels is determined by its thickness which is contributed by the core thickness. Because the flexural stiffness of the panels is proportional to the cube of their thickness, stiffness of sandwich panels can be easily increased by thickening the core of a low-density material.

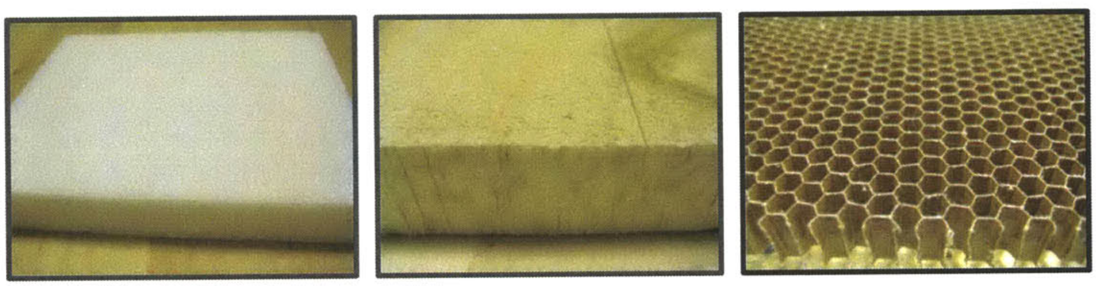


Figure 1-2: Existing core materials: foam, balsa wood, and honeycomb

The one of main common limitation of the existing core materials is a low structural freedom. Balsa wood, foams, and honeycombs are used to fill a flat plane since they are fabricated as a form of flat panels with variances of thickness. Even though they have suitable properties as core materials, the flat shape of existing core materials constrains their versatile use for construction. Balsa wood can be described as 'nature's honeycomb', because it has a structure similar to the cellular hexagonal structure of a synthetic honeycomb on a microscopic scale. However, they should bonded after cutting into small pieces of the same thickness due to the limitation of size of the cross section of balsa wood in order to cover a huge plane of the structure with vertically arrayed grains. Despite their low density and excellent thermal property as insulation materials, there exists a tradeoff between cost and mechanical properties of the foams and the fire safety of the foams is much lower than other core materials. Honeycombs are very light and strong against compression, however their structural limitation, high cost and difficulties in fabrication block their wide usage.

1.2. Goal

Sandwich structures tend to be limited to a small range of material combinations. For example, a metallic core is generally combined with a metal facing; a composite face such as GFRP, CFRP are usually coupled with a polymeric foam core or a non-metallic honeycomb. The better performance and economic, environmental benefits could be possibly achieved by using hybrid sandwich panels comprising non-traditional pairs of materials.[3] Therefore, in this paper, cork-based plastic composite is proposed as a new core material and the possibility for substituting the existing core materials are explored by investigation on their mechanical properties, economic benefit, and environmental impact.

1.3. Overview

Chapter 2 describes the general requirements to carry out material design. Material design requires functional property profile; cost; and eco-impacts of newly developed materials. The cork-based plastic composite material is proposed as a new core material.

Chapter 3 reviews mechanical properties of the cork composite in order to check their functional property profile. Several mechanical testing are conducted to determine the mechanical properties of the cork composite. It also describes simple design approaches in such a way that obtained properties are independently considered. Stiffness - limited, yield - limited, and fracture toughness - limited design case are reviewed using determined mechanical properties.

Chapter 4 reviews economic competitiveness of the cork composite with other core materials with a panel application. Under the assumptions that the rigidities of the panel are identical, the costs of manufacturing each core material are compared by calculating requiring thickness of the panel application.

Chapter 5 reviews environmental impact of the cork composite. Life cycle assessment (LCA) of cork composite is performed to prove environmental benefit of using it over other core materials especially Glass Fiber Reinforced Plastic (GFRP).

Chapter 6 presents a concluding remark of this thesis. Future directions of research are discussed.

Chapter 2 Material design

2.1. Overview on material design

Material selection has each stage of considerations interacting vertically/ horizontally. The performance of a component is limited by certain of properties of materials of which it is made since the values of the design-limiting properties of integrated structure should meet certain level of performance. Therefore, when materials are designed or chosen, identifying design requirements for specific purpose or applications should be done first. [4] Constraints on choosing materials such as required property profile and required shape will help screen out the materials that do not meet the design-limiting properties. Final decision is made on choosing the material for specified purpose after ranking the materials, process, investigating costs and eco-impact. Figure 2-1 represents these procedures and interactions between design requirements, material, shape and process for specified goals.

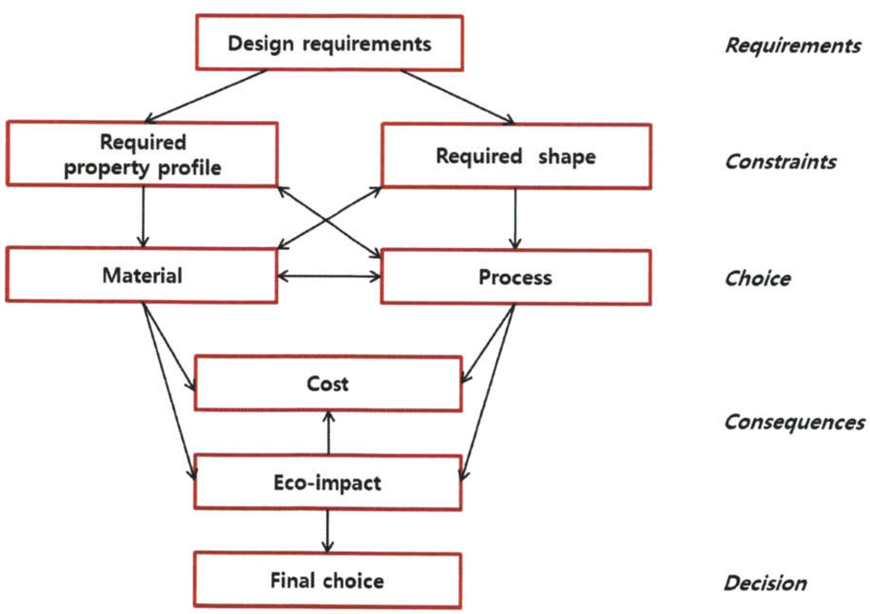


Figure 2-1: The interaction between design requirements, material, shape and process[4]

2.1.1. Design requirements

Engineering components have their own functions. For example, they should support a load; contain a pressure; and transmit heat, so on. These functional requirements should be translated into constraints. Certain dimensions of components, level of load that they can carry without failure, range of temperature that they can function can be the constraints. A constraint is condition that must be met. Common constraints are meeting a target value: stiffness, strength, fracture toughness, thermal conductivity, cost, and mass, etc. [5]. Normally as constraints are applied, the material search space is narrowed down as illustrated in Figure 2-2.

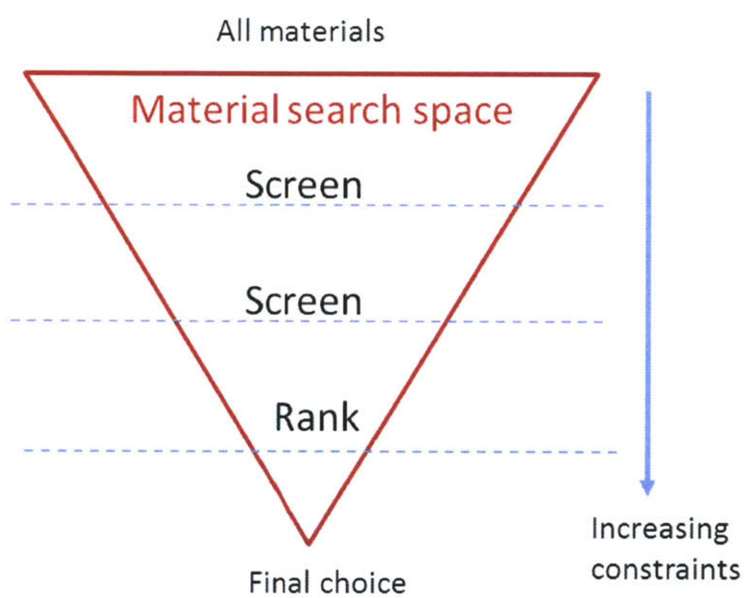


Figure 2-2: The narrowing of material search space as design constraints are applied.[4]

Objective of design problem is for example, to make it as light as possible, or as cheap as possible. Thus, objective can be expressed as equation or inequality and certain parameters can be altered to optimize the objective. These certain parameters are referred as free variables. Constraints, objective and free variables define the boundary conditions for selecting a material

2.1.2 Material

It is conventional to classify engineering materials into six families: metals, polymers, elastomers, ceramics, glasses and hybrids. *Metals* have high stiffness. Most of them are easily deformed and tough which means they have high fracture toughness K_{1c}. *Polymers* are organic solids on long chains of carbon or silicon atoms. They are light but strong so their strength per unit weight is comparable. They are easy to shape and to be molded for complicated parts. *Elastomers* have uniquely low stiffness, so their stretching ability makes it recover to initial shape when released. *Ceramics* are stiff, hard non-metallic, inorganic solids. They resists well against corrosion and high temperature. *Glasses* are amorphous solids, but they are brittle and vulnerable. *Hybrids* are combination of two or more materials so their properties can be manipulated for intended use. Figure 2-3 gives an overview of the physical and mechanical properties of materials presenting the information in a compact way.

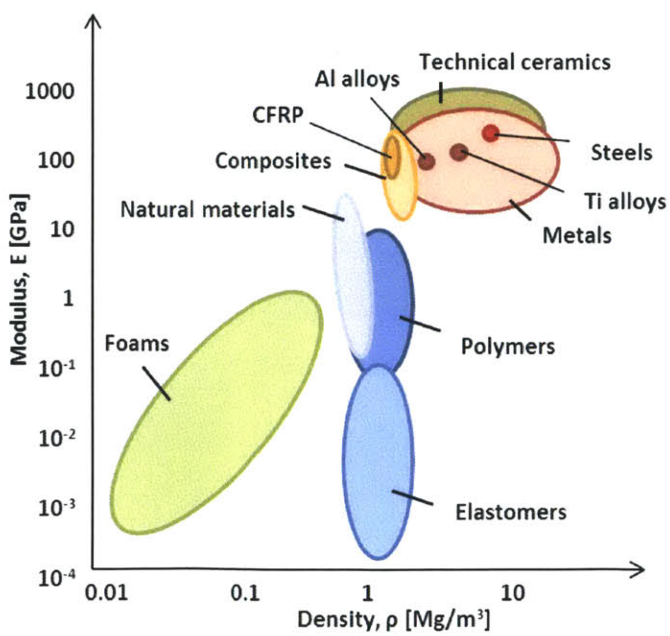


Figure 2-3: The modulus-density chart

2.1.3. Process

A process is a method of shaping, joining and polishing a material, thus casting, injection molding, and fusion welding are typical types of processes. Actually there exist hundreds of processes for materials to be processed. However, it is important to choose the right process at early stage in the design before cost-penalty becomes large. [4] Process choice is influenced by the material: by its formability, machinability, weldability, heat treatability and so on. Process choice is also influenced by the requirements for shape, the size, the precision and, to a large extent, the cost of a component. Processing can change the property of materials. However, composites such as Glass Fiber Reinforced Plastic (GFRP), Carbon Fiber Reinforced Plastic (CFRP) have no useful properties at all until processed.

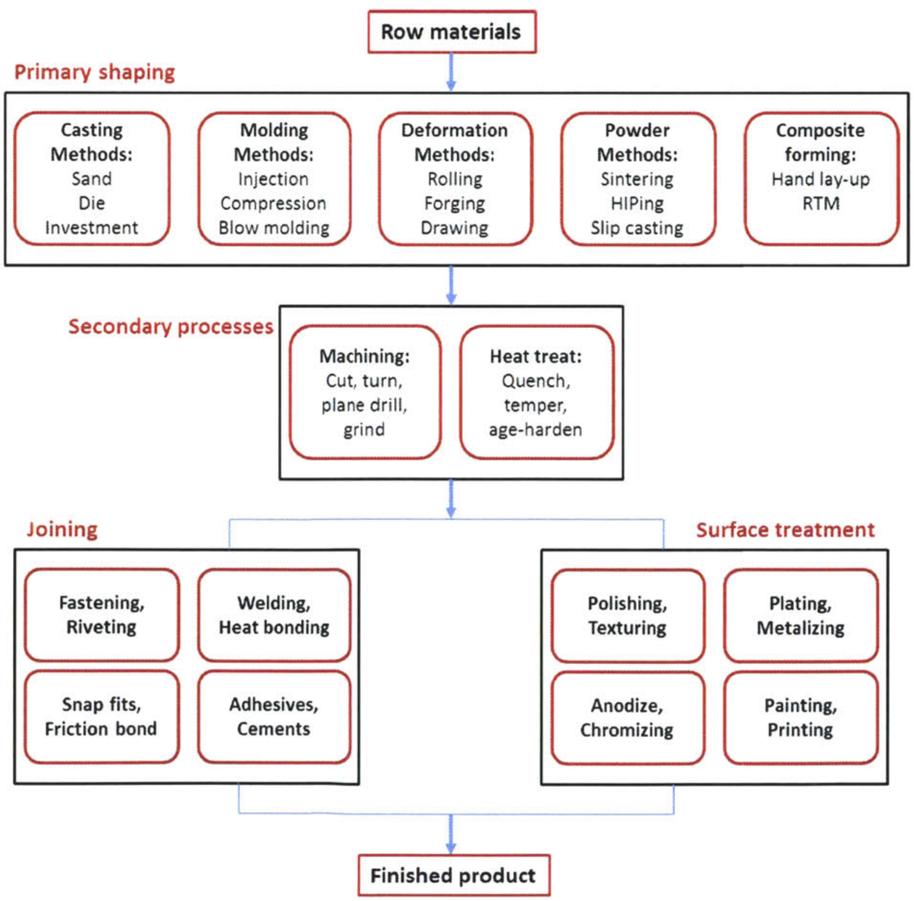


Figure 2-4: The class of process [4]

2.1.4. Cost

Cost is an important factor for choosing materials. Often minimizing cost is overriding objective of a design. In general cost includes material cost, manufacturing cost or sometimes even transportation. Concrete and wood are the cheapest; polymers steels and aluminum alloys come next and special type of metals like titanium, ceramics and few polymers are expensive.

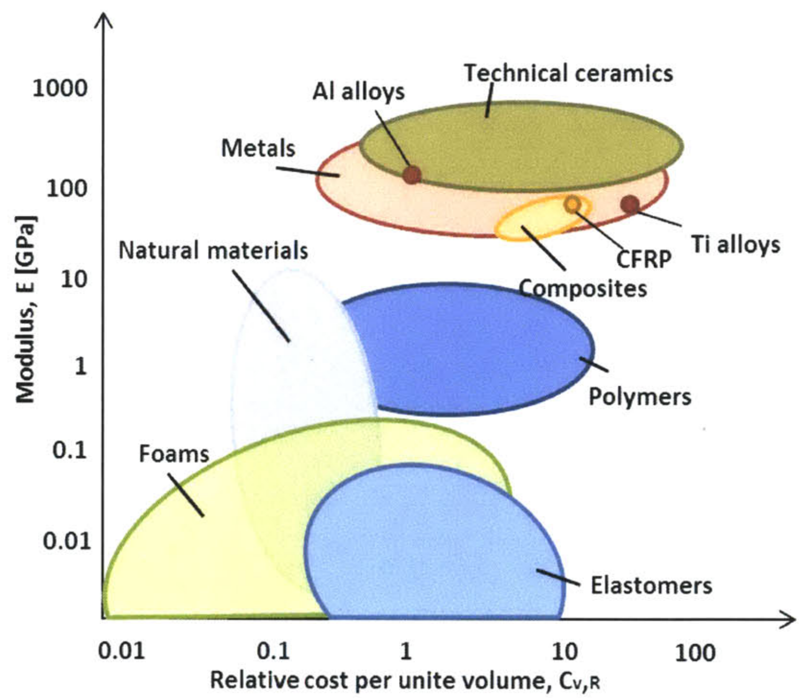


Figure 2-5: The relative cost per unit volume-modulus chart

2.1.5. Eco-impact

For the selection of material, the environmental responsibility is sometimes passed unnoticed. However, the age of components inevitably requests the replacement of them with new components and it should be reminded that all these activities make impact on the environments. Life cycle assessment (LCA) is an analytical approach to help in the evaluation of the environmental implications of products, processes, and services. [7] LCA evaluates all relevant environmental, economic and technical issues associated with a material, product and process throughout its entire life. Therefore, it is considered that LCA approaches can help people to assess the environmental issues associated with products. Also it can guide people choose more environmentally conscious products materials, components or even services by providing a single indicator.

2.2. Design proposal

2.2.1. Cork –based plastic composites design proposal

The similar strategy described in material selection can be adapted to design new core material. Not only just developing a new material that meets the functional requirements, but also investigations on all aspects should be conducted to see synthetically whether it meets the level of functional requirements, existence of economic benefits in terms of cost for manufacturing and environmental effects of using it.

Cork is a natural product obtained from the outer bark of the cork oak. It is light and does not absorb water. It also has very low thermal conductivity which makes it a good insulator, and has excellent energy-absorbing capacity. Due to its elasticity and impermeability cork is mostly used as a bottle stoppers, especially for wine bottles. Using Cork as stoppers for bottles is one of the traditional ways to consume cork and it still takes about 60% of all cork based production[8],[9]. Its applications have been restricted to traditional sectors, not having reached all of its potential use. Recently, development of new cork materials in composites has been studied to use its good properties for structural applications.

In this study, we mainly focus on the cork composite core material design with concerns of meeting functional requirements, cost attractiveness and less environmental impacts.

2.2.2. Design requirements

The concept of sandwich panels is similar with I-beams. The horizontals element of I beams are flanges while the vertical element is called web. The web is supposed to resist well against shear force and flanges resist most of the bending moment. It is proved by the beam theory that the I-shaped section is efficient to carry high bending and shear loads. In sandwich panels, facings usually take most of bending applied and core resists shear loads. [1] Therefore, shear properties of core material are important. It is known that as core thickness increases double, total stiffness of a sandwich panel increases 7 times. If we want to keep this structural efficiency of sandwich panels, it is clear that core should be light. Other mechanical properties such as compressive, fracture toughness properties are also important since sandwich panels are normally used for structural applications. Corrosion resistance and breaking toughness rigidity are also critical factors. [6]

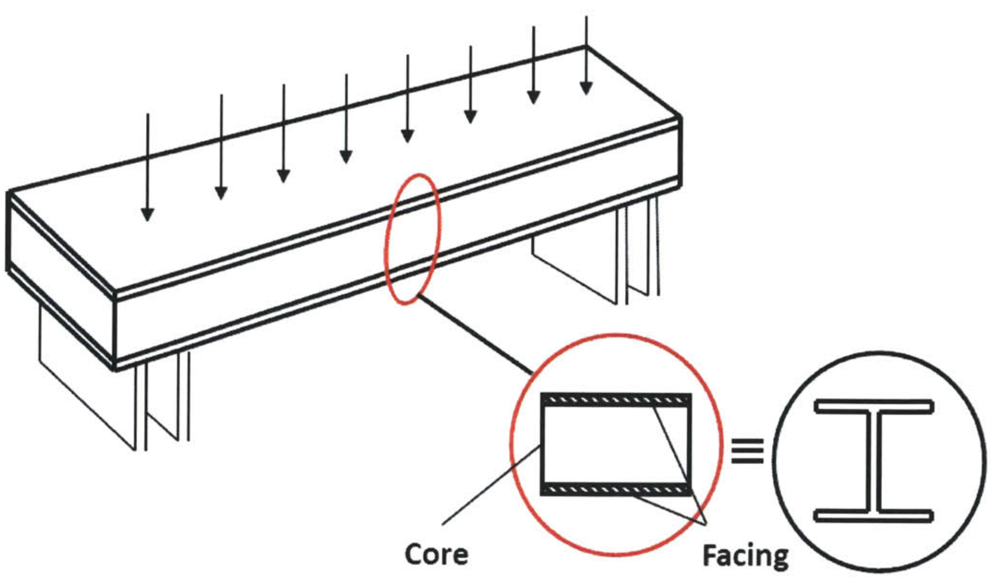


Figure 2-6: The concept of a sandwich panel is similar with an I-beam.

2.2.2.1. Required property profile

First, the stiffness and strength of cork composites should be determined in order to characterize its basic properties as a newly synthesized material. As specified above, several mechanical properties important for core materials such as compressive, and shear properties should be evaluated. Under the consideration that cork composite will be functioned inside sandwich panels, mechanical properties which are important for structural applications should be investigated as well. Fracture toughness, water absorption tests are recommended to conduct.

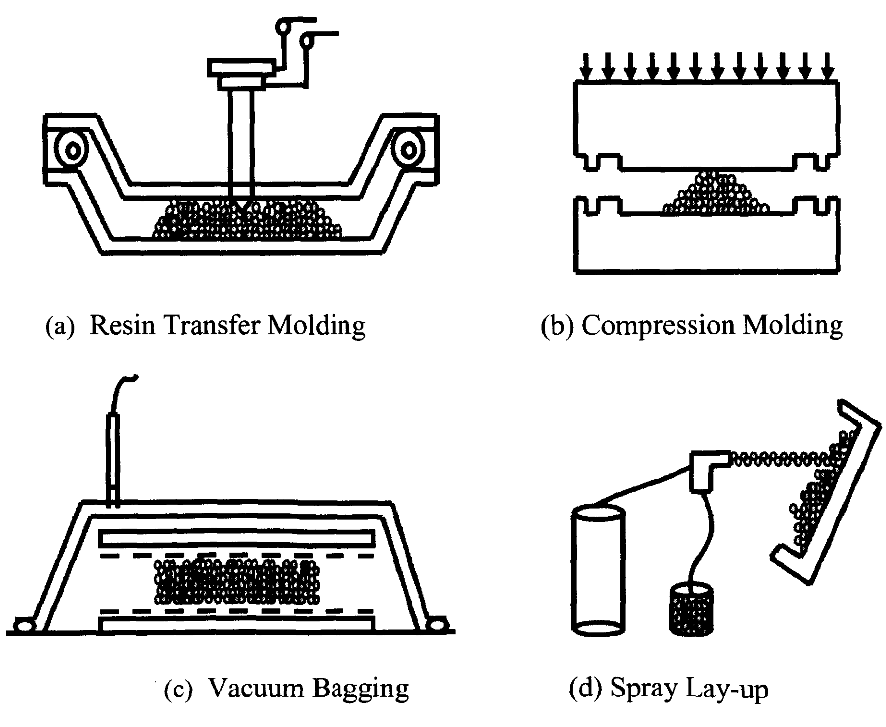
2.2.2.2. Material selection

Most materials utilized as a core material have density less than 1 Mg/m^3. There are few materials have not been used as a core material and cork is one of them that have attractive features for core materials. The characteristics of cork that attracts us to use it as a core material were already overviewed. In summary, it has a low density, good corrosion/fire resistance, and low thermal conductivity. The cork granules are provided from the company named Corticeira Amorim, from Portugal. Three different sizes of cork granules are given; 1mm, 2mm, 3mm.

The cork composite needs a binder to hold them together. There are two different types of polymer matrix: thermoset(epoxy, polymide, polyester) and thermoplastic (Poly-ether-ether- ketone (PEEK), polysulfone). Among polymer matrixes, thermoset are preferred over thermoplastics since thermoplastics soften at high temperature. What matrix does in a composite structure is to bind cork granules together and keep the structure from external damage, transfers and distributes the applied loads inside the core. A strong interface bond between cork and matrix is desirable, thus the matrix must be capable of developing a strong mechanical or chemical bond with core. The matrix materials should be selected together in order to prevent chemically undesirable reaction at the interface. Therefore, epoxy is chosen as a matrix for the cork composites due to its high mechanical properties and its chemical stability.

2.2.2.3. Process selection

Under the consideration of interrelation shown in Figure 2-7 and the fact that cork composites will be comprised of cork granule and epoxy binder, there are 4 possible candidates of manufacturing processes that can be applied to fabricate the cork composites. Table 2-1 summarizes the comparison of advantages and disadvantages of each narrowed down manufacturing processes. Since the cork composite study is at an early stage, exploring the possibility of the cork composite as a core material, mass production of complicated structure with the cork composite is unnecessary. Therefore vacuum bagging process is chosen as a manufacturing process due to its low equipment cost and medium part strength.



(a) Resin Transfer Molding (b) Compression Molding

(c) Vacuum Bagging (d) Spray Lay-up

Figure 2-7: Various types of processes can be applied to fabricate particulate composites.

Table 2-1: The comparison of manufacturing process.

Manufacturing process	Equipment Cost	Rate of production	Part strength	Reproductibility	Part complexity
Resin Transfer Molding	Medium	Medium	N/A	High	High
Compression Molding	High	High	N/A	High	High
Vacuum Bagging	*Low*	*Medium*	*Medium*	*Low*	*High*
Spray Lay-up	Medium	Medium	Low	High	High

2.2.2.4. Economic approach

Sandwich structure is a hybrid material, which is a combination of two (or more) materials in attempt to get the best properties of both. It is known that hybrid components are expensive and they are relatively difficult to form and join which means expensive for fabrication. Therefore, sandwich structure may be used only when the added cost justifies added performance or other benefits in eco-impact. The unit price of cork is cheaper than other core materials. However, it needs a binder material and polymer binder is relatively expensive. Since cost is a significant factor for choosing materials, the unit price of core materials including cork composites should be compared to offer price information.

2.2.2.5. Environmental approach

Other than balsa wood, most existing core materials are not natural materials. Some of them are synthesized from toxic chemicals and others are made of metals. Cork is a natural material that can be utilized as a core material in a sandwich panel. Therefore, it is expected that it loads less environmental burdens than other core materials. Environmental burdens of using different core materials should be assessed.

2.2.3. Designing and Manufacturing cork composites

2.2.3.1. Manufacturing procedure

The cork composites are prepared in rough accordance with the ASTM D5687 procedure. Flat molds, two pieces of plywood covered by packaging tape, are used to make both samples. A layer of release fabric was placed on the bottom mold piece which is impermeable by tape, followed by lay-up, another layer of release fabric, breather material, the upper mold piece and more breather material to reduce sharp edges under the bag. Figure 2-8 shows the setup.

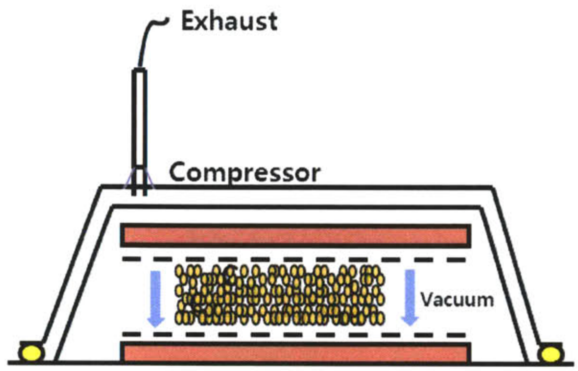


Figure 2-8: Vacuum bagging setup as a selected process

Composites are cured under the evenly distributed pressure at 70psi for seven hours and should be remained without pressure for another seven hours for fully curing of the epoxy. Cork composites can be categorized into particulate composite with thermoset matrix (epoxy). The chosen epoxy resin (West System, USA), biphenol-A type and an aliphatic polyamine hardener (West System, USA) has a low viscosity (950 mPa s) and flexural strength of 90~100 MPa. For the curing process at a room temperature of 25°C, the hardener was mixed with the epoxy resin at a volume ratio of 1:5. Table 2-2 and 2-3 provide physical and mechanical properties of cork and epoxy used for this study.

Table 2-2: The physical and mechanical properties of cork

Material	**Cork**
Diameter(mm)	1-3
Density (kg/ m^3)	60
Tensile strength (MPa)	1.5
Tensile modulus (GPa)	0.032
Compressive strength(MPa)	1-26

Table 2-3: The physical and mechanical properties of epoxy

Material	Epoxy
Density (kg/ m^3)	1,100
Viscosity(cPs)	1,000
Tensile strength (MPa)	54
Tensile modulus (GPa)	2.81
Thermal conductivity(W/(m·K)	0.35

2.2.3.2 Manipulating modulus and density

Composites made by embedding fibers of particles in a matrix of a polymer, metal, or ceramics have high stiffness and strength per unit weight. [10] When a volume fraction f of a reinforcement r (density ρ_r) is mixed with a volume fraction $(1\text{-}f)$ of a matrix m (density ρ_m) to form a composite, the composite density ρ_c follows rule of mixture in equation (1). Geometry or shape of the reinforcement does not matter.

$$\rho_c = f\rho_r + (1-f)\rho_m \qquad (1)$$

It is known that modulus of composites also follows the rule of mixture, but it is bracketed by two bounds. [4] The upper bound, E_U can be calculated based on assumption that the two components strain by the same amount. This can be understood like springs in parallel. E_r is the Young's modulus of reinforcement and E_m that of the matrix.

$$E_u = fE_r + (1-f)E_m \qquad (2)$$

The lower limit can be calculated by assuming that the two components carry the same stress, like spring in series.

$$E_L = \frac{E_m E_r}{fE_m + (1-f)E_r} \qquad (3)$$

Figure 2-8 shows the range of cork composite properties that could be lying in the density-Young's modulus, depending on the volume fraction.

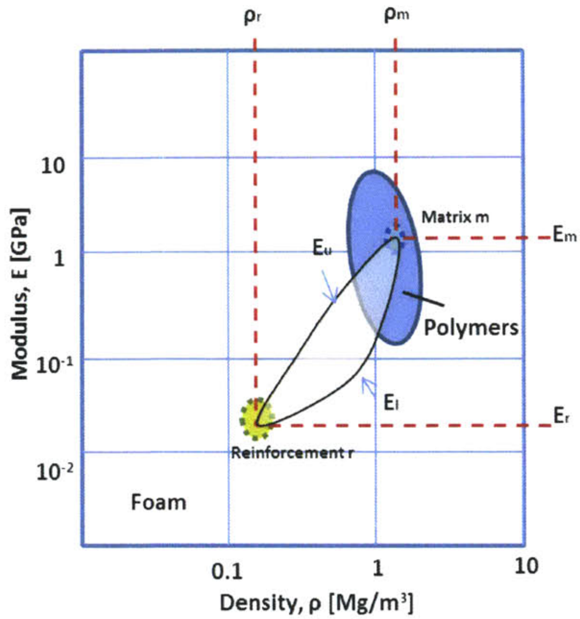


Figure 2-9: Density and modulus ranges of composites made form a matrix m with a reinforcement r

Even though strong correlation of volume fraction and stiffness of the composites can be seen from equations (2), (3), the fiber volume fractions are roughly determined by molding processes that can be used for making composites. Table 2-4 shows common fiber volume fractions in different processes.

Table 2-4: Fiber volume fraction in different process [6]

Molding Process	f (%)
Contact Molding	30%
Compression Molding	40%
Filament Winding	60%~85%
Vacuum Molding	50%~80%

2.2.3.3. Design parameter variation

Size of Cork Granules

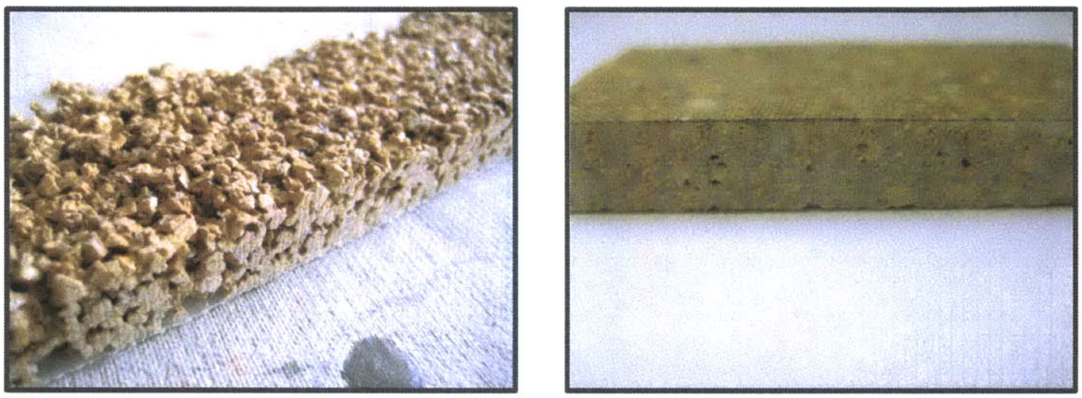
For this study, we have three different sizes of granulated cork: 1mm, 2mm, 3mm, as shown in Figure 2-10. Cork composites using one size of cork granules have gaps and these gaps are usually filled with matrix which results in making cork composites less dense with cork granules. Considering that the cork composites follows rule of mixture, the mechanical properties of cork composites should only be affected by the volume fraction, not by the size of cork granules. However, it was revealed that blending different size of cork granules gives better properties, due to better inter-particle bonding even though the same amount of cork were used inside the composites.[11] Therefore, different sizes of cork granules are mixed and tested to check which combination has the closest value to theoretical one that can be calculated by equation (2).

(a) (b) (c)

Figure 2-10: Cork granules: (a) 3mm, (b) 2mm, and (c) 1mm

Volume fraction

During fabrication process, it had already been noticed that there is a critical amount of epoxy resin beyond which, further additions of epoxy resin, causes to an unnecessary wetting situation. For cork composites in this study, the optimum amounts of epoxy are determined by trials. If less epoxy is added to the cork combinations, the entire composites couldn't coat themselves well within amounts of epoxy added. However, due to the characteristics of the vacuum bagging setup, exceeding the critical amount of epoxy resin was likely to slip out from the aggregates rather than hold them and this slipped out epoxy doesn't affect composites volume faction actually. This happens because once amounts of cork granules in the composites are determined the ultimate gaps between cork granules cannot be changed and are filled with some amounts of epoxy that needed to fill those gaps. Figure 2-11 shows the cork composites without enough epoxy. Thus, it is found that the volume ratio which shows optimal wetting ability for epoxy resin is 0.65 in this study. If other casting processes which can adjust volume ratio for the cork composites are suggested such as Resin Transfer Molding, it would be worth to check Kelvin-Voigt model for the rule of mixtures.



(a) (b)

Figure 2-11: Cork composites with volume fraction ratio f (a)>0.65, (b) 0.65

Additional Fillers

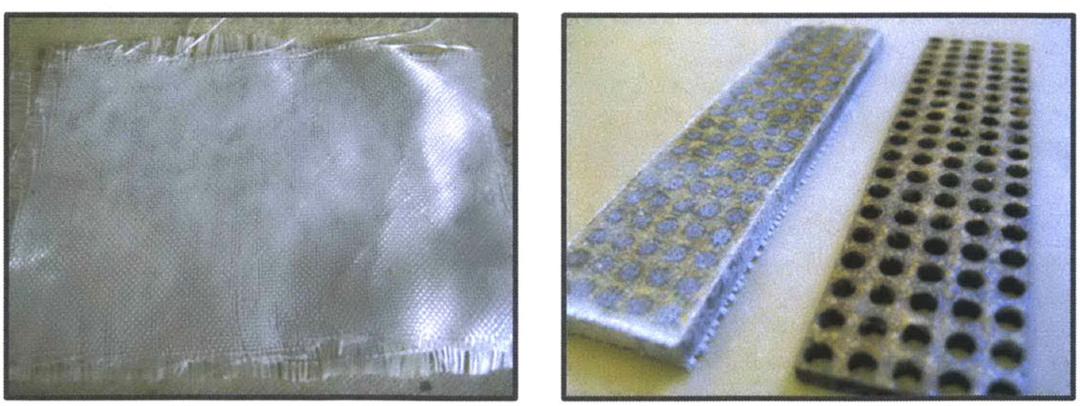
Considering the possible usage of cork composites as a structural material, two types of additional fillers, micro fiber (West System), a silicon dioxide cotton flock, and chopped glass strand (System Three Resins, Inc.) are mixed with the cork composites in order to fortify the mechanical properties. It is different in the way that they improve the properties. Micro fiber is supposed to improve the internal bonding of constituent materials while chopped glass strand is supposed to introduce complicated structure inside. However, their added amounts into the composites are restricted not to exceed the amounts of cork granules by volumes. The ratio of cork granules to fillers varies 1/4 to 1/2 in this study.

(a) (b)

Figure 2-12: Cork granules with additional fillers (a) Micro fiber, (b) Chopped glass strand

Facing

The most possible application of the cork composites is being used as a core material inside sandwich panels. In order to see the effects of facing on the composites and their mechanical behaviors as a whole sandwiched structure, E-glass woven fabrics which has the same properties in both warp and weft directions for skin materials from West system, are added onto both sides of the cork composites as a facing material.



(a) (b)

Figure 2-13: (a) E-glass woven fabric, (b) sandwiched cork composite with E-glass woven fabric and cork composite core without facing

Table 2-5: The physical and mechanical properties of epoxy

Material	Woven fabric
Density (kg/m^3)	3,000
Tensile strength (MPa)	206
Tensile modulus (GPa)	17.23
Thermal conductivity(W/(m·K)	0.04

Chpater 3 Experiments and Analysis

3.1. Mechanical properties analysis

3.1.1. Bending test

3.1.1.1. Background theory

The experiments data recorded only have applying loads to specimen and displacements of specimen correspondingly. For the composites in this study, the specimens are deflected until rupture occurs either in the outer surface of the test specimen or on entire specimen. The Flexural stress from the test can be calculated by the equation from ASTM D790.[12] The flexural strength is the maximum flexural stress during the bending test.

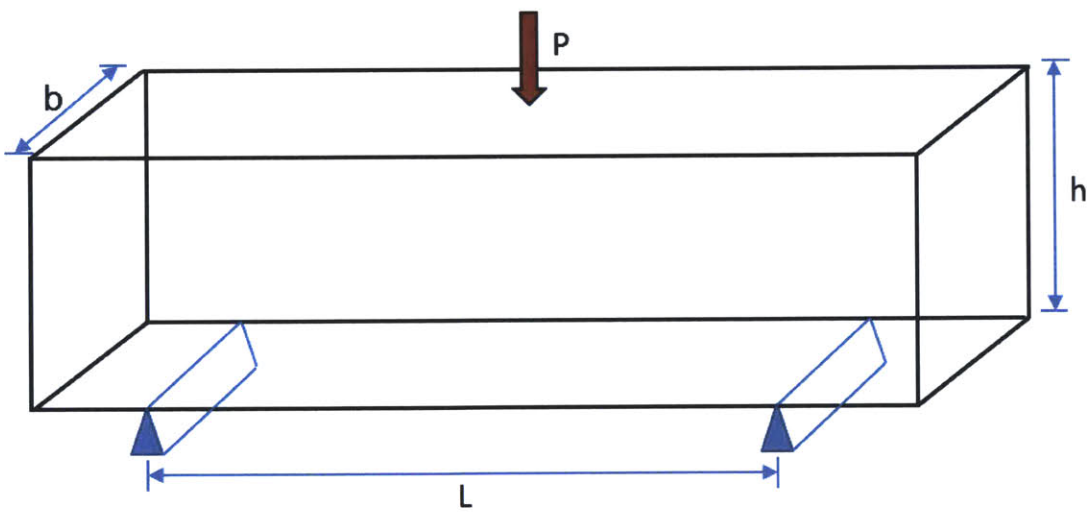


Figure 3-1: A specimen for bending test

$$\sigma_f = \frac{3PL}{2bh^2} \quad (4)$$

Where

σ= stress in the outer fibers at midpoint

P = load at a given point on the load-deflection curve

L = length of the support span

b = width of beam

h = thickness

The flexural strain indicates that changes in the length of an element of the outer surface of the test specimen at midspan by flexural stress. The flexural strain is also calculated by using equation (5).

$$\varepsilon_f = \frac{6Dh}{L^2} \qquad (5)$$

Where

ε_f = strain in the outer surface,

D = maximum deflection of the center of the beam,

L = the length of the support span, and

h = thickness.

The flexural modulus of elasticity, often called the "modulus of elasticity," is the ratio of stress to corresponding strain within the elastic limit. It is calculated by following equation. (6)

$$E_b = \frac{L^3 m}{4bd^3} \qquad (6)$$

Where

E_b = modulus of elasticity in bending

L = the length of the support span

b = the width of beam tested

d = depth of beam (same as thickness of beam h)

m = slope of the tangent to the initial straight-line portion of the load-deflection curve

Theoretical density and modulus of cork composites

By referring the table 2-2 and 2-3 for physical and mechanical properties of cork and epoxy, the theoretical density and modulus of the cork composites can be calculated using equation (1), (2), and (3). The volume fraction of the cork composite, f, is set up to be 0.65.

Table 3-1: Theoretical ranges of density and modulus of the cork composite

Property	Theoretical values
Density ρ_c (Mg/m^3)	0.424
Modulus E_L~E_U (GPa	0.05~1

3.1.1.2. Experimental setup

Testing protocol was based off of the ASTM D790 procedure, which covers the determination of flexural properties of unreinforced and reinforced plastics.

Apparatus

The Instron 1125, modified by ADMET to include load control, is the test machine with a 20kN loading cell. The appropriate strain rate is calculated according to ASTM D790.

$$R = \frac{ZL^3}{6h} \qquad (7)$$

Where,

R = rate of crosshead motion, i.e. strain rate,

L = support span

h = the thickness of beam tested

Z = rate of straining of the outer fiber, mm/mm/min. Z shall be equal to 0.01.

The strain rate is changed for each sample group after measuring the thickness of each samples and averaging them. The support span is 90mm for the specimens that have a span-to-thickness ratio greater than 16:1. The radii of the supports are 12.7 mm and that of the loading nose was 19 mm, differing from the 5mm radii called for by the protocol. Each sample group should be tested with at least 5 specimens.

Specimen

The specimens are machined down to the length of 100mm, and width of 25mm. Even the thickness of the specimens differs from not only each sample group and also each specimen in the same group, they are relatively thin compared to their length, less than 1/16 times of their length.

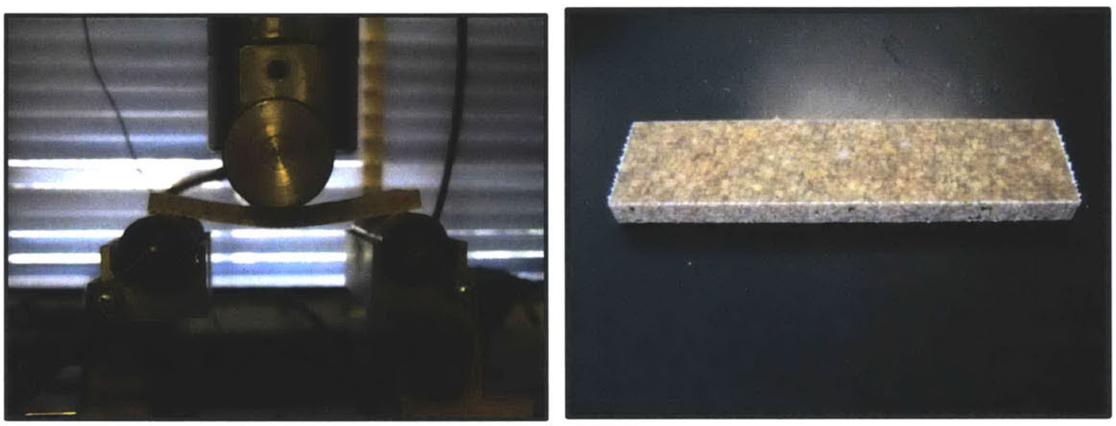


Figure 3-2: Apparatus and specimen for bending test

3.1.1.3. Results and analysis

Influence of the cork granule size on the mechanical properties

During fabrication process, it had already been noticed that there is a critical amount of epoxy resin beyond which, further additions of epoxy resin, causes to an unnecessary wetting situation. Due to the characteristics of the vacuum bagging setup, exceeding the critical amount of epoxy resin was likely to slip out from the aggregates rather than hold them. Thus, it was found that the volume ratio which shows optimal wetting ability for epoxy resin is 0.65 in this study. If other casting processes which can adjust volume ratio for the cork composites are suggested such as Resin Transfer Molding, it would be worth to check

Kelvin-Voigt model for the rule of mixtures.

Since three different size of cork granules (1mm, 2mm, 3mm) were provided for this study, the effect of size of cork granules on the mechanical properties were examined by tensile and bending tests. It was revealed that blending different size of cork granules gives better properties, due to better inter-particle bonding even though the same amount of cork were mixed inside the composites.

The results in table 3-1 show the mechanical properties dependence on cork granule size. The greatest bending strength and modulus were presented by the combination of 1mm and 3mm cork granules. Comparing four combinations of the cork composites, the combinations that contained cork size 1mm tended to have relatively higher properties compared to the combination that excluded the smallest size. The fact that the cork composites that contained the smallest size have higher mechanical properties appeared to be related with the gap filling inside the composites. In Figure 3-3, it was observed that smaller size of cork granules fill the gaps between granules more tightly, giving more contact points between cork granules while bigger cork granules have difficulty of filling the gaps. Even though the epoxy resin took over the rooms between cork granules, but bigger size granules seemed to cause the occurrence of premature micro-cracking of epoxy/cork interface when the load was applied.

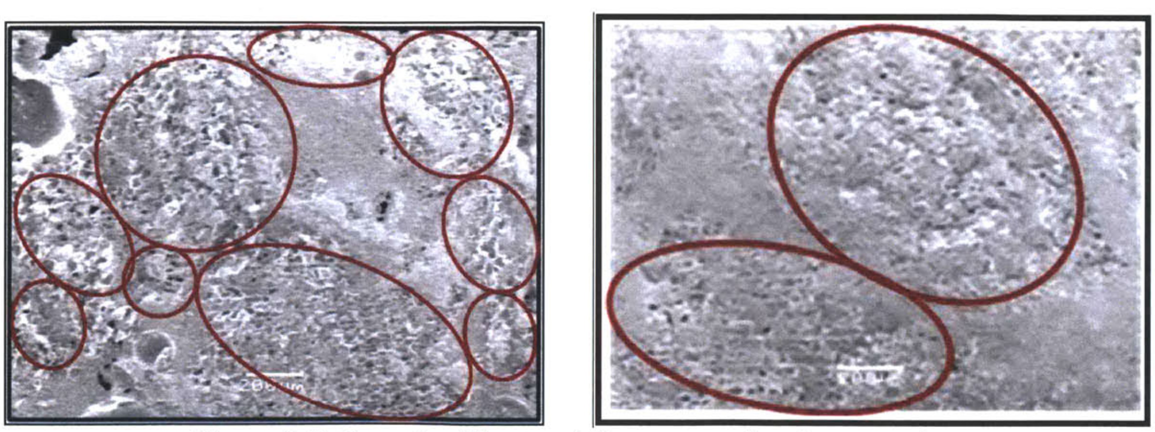


Figure 3-3: Scanning Electron Microscope of cork composites

Table 3-1: Mechanical properties of cork composites with different granule size

Test series	Physical and mechanical Properties		
	Density (Mg/ m^3)	Flexural strength (MPa)	Flexural modulus (GPa)
1,2mm	0.58	11.53	0.52
2,3mm	0.58	7.52	0.38
1,3mm	0.58	11.58	0.54
1,2,3m	0.58	10.40	0.50

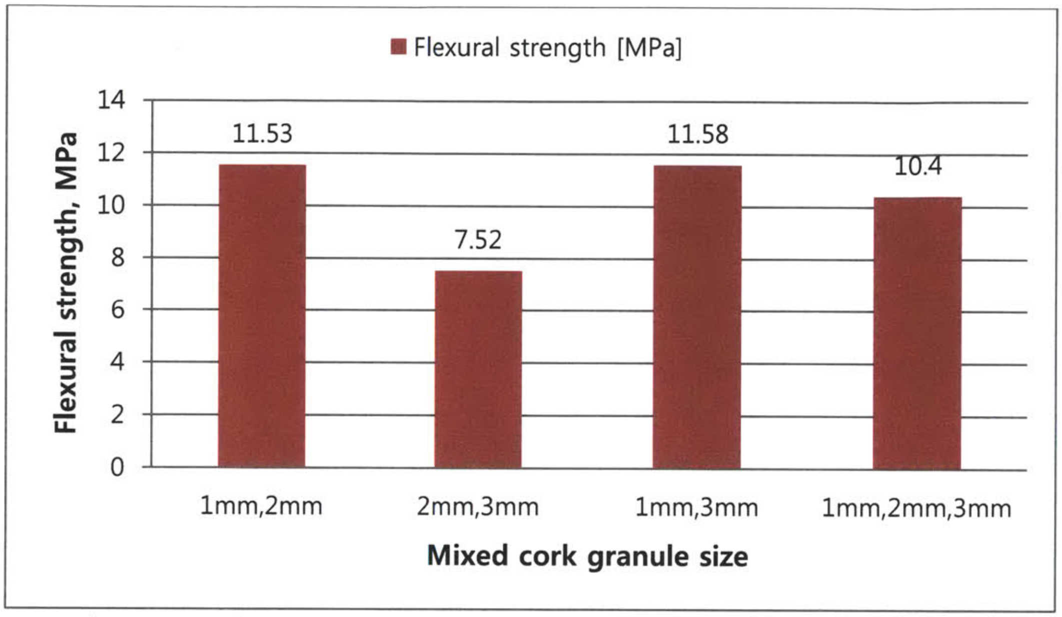


Figure 3-4: Flexural strength of cork compsoite with different granule size

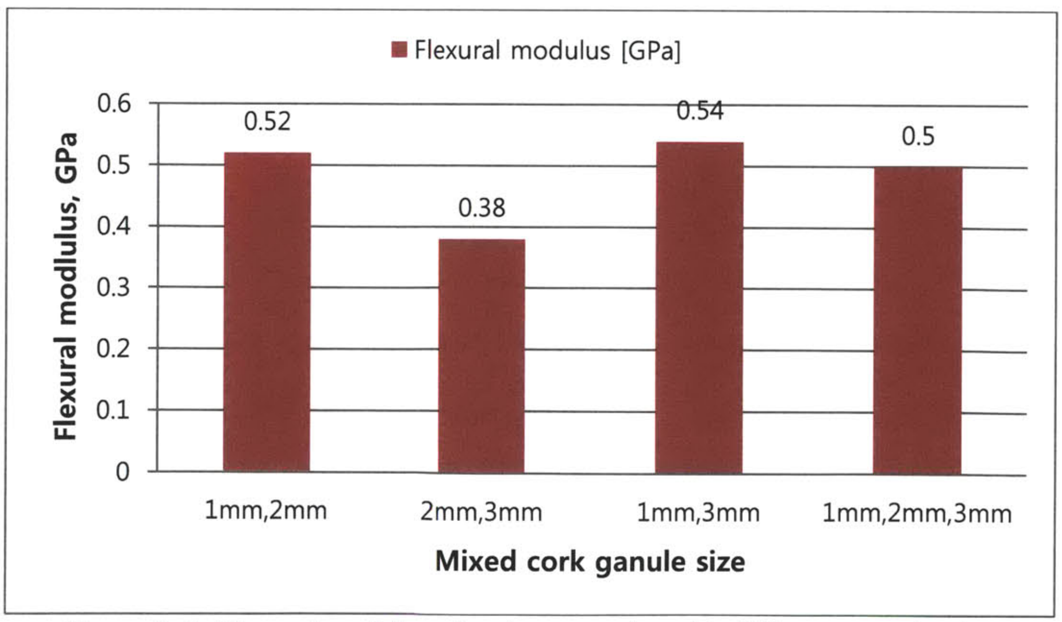


Figure 3-5: Flexural modulus of cork compsoite with different granule size

As we compare the results with the theoretical ones, we could find that difference between the theoretical ones and experimental ones exists. Based on the rule of mixture and the physical properties of constituent materials, the theoretical density of cork composite is 0.424 Mg/m^3, but the experimental one turned out to be 0.58Mg/m^3. When theoretical one calculated, the value is idealistic since it doesn't account a real squeezing action in the vacuum bag in the fabrication process. When vacuuming happens, cork granules tend to shrink their size since many empty rooms are inside a cork granule which makes cork's Poisson ratio zero and resin takes the volume which is from decreased cork size. These all actions seemed to make the density higher than it would be.

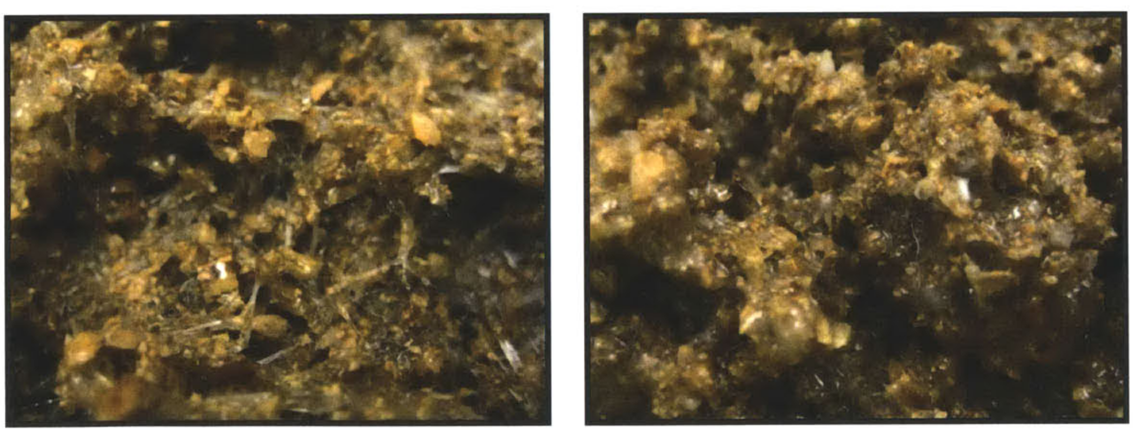
Influence of additional fillers on the mechanical properties

Considering the possible usage of the cork composites, the cork composites were needed to improve properties. Two different ways of improving properties were suggested: improving internal bonding of constituent materials; introducing higher mechanical properties from additive. In an attempt to assess the suggested method of fortifying mechanical properties, two different types of fillers were added to the pure cork composites (cork and epoxy resin only): micro fibers and chopped glass strand. From the results of the influence of the cork granule size, additional fillers were added on the combination of 1mm and 3mm cork granules. Their added amounts into the cork composites were restricted not to exceed the amounts of cork granules by volume. Thus, the ratio of cork granules to fillers was fixed by 3:2 for bending test to see the effect of fillers and the binder ratio was still set up at 0.65.

Bending tests were done to examine which filler improves mechanical properties of the cork composites better. The influence of the additional fillers is shown in Table 3-3. For bending properties, micro fibers increases with values of 23% and 72% in strength and modulus respectively whereas chopped glass strand deteriorated the bending properties with values of

21% and 17% in both strength and modulus.

It was observed that micro fibers becomes sticky and fluidic when they wet through resin which gave strong inter-particle bonding in the cork composites improving adhesion of cork and epoxy regardless of the loading direction to specimens. It was confirmed that this strong inter-particle bonding introduced by micro fibers was successful for improving bending properties. Due to higher mechanical properties of chopped glass strand, it was therefore expected to deliver their mechanical properties to the cork composites by forming stronger and more complicated constituent structures with cork granules and epoxy. This hypothesis showed partial agreement on tensile properties. However, it showed weakness against the bending force against expectation, and it seemed related the fact that the arrays of chopped glass strand inside the cork composites were perpendicular to the applied load which blocked demonstrating their high mechanical properties along lengthwise. The chopped glass strand made the internal bonding weaker in the cork composites, and even deteriorated their bending properties compared to the pure cork composites.



(a) (b)

Figure 3-6: Cork granules mixed with epoxy and (a) chopped glass stranded, (b) micro fiber

Table 3-3: Mechanical properties of cork composites with different additional fillers

Test series	Mechanical Properties		
	Density (Mg/m^3)	Flexural strength (MPa)	Flexural modulus (GPa)
Pure cork composite (1,3mm)	0.58	11.58	0.54
Chopped glass strand added	0.62	9.12	0.45
Micro fibers added	0.67	15.02	0.93

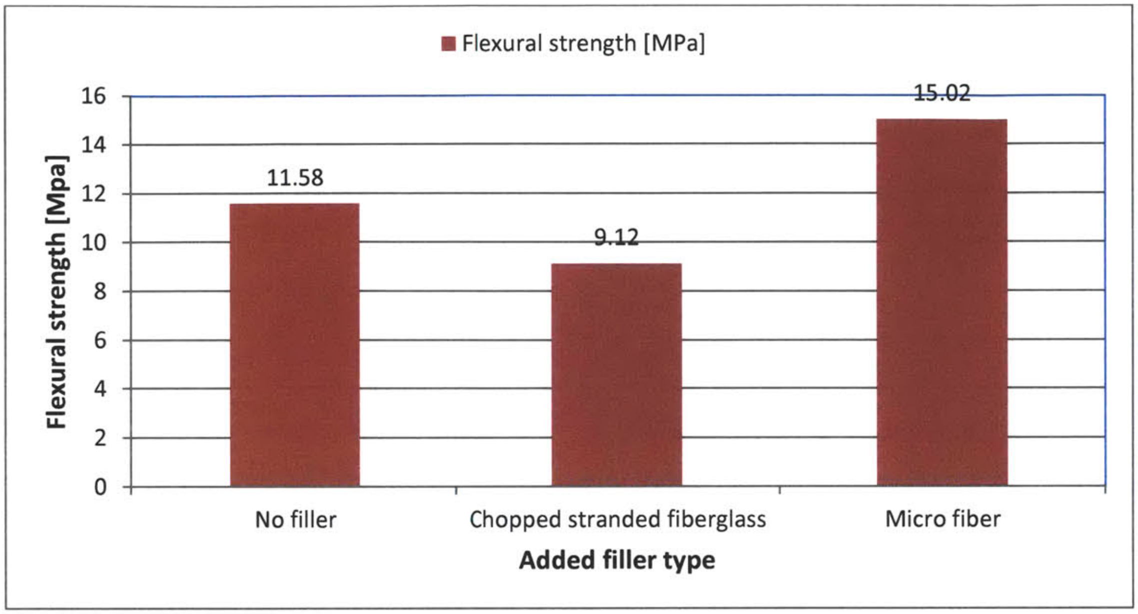


Figure 3-7: Flexural strength of cork compsoite with different filler type

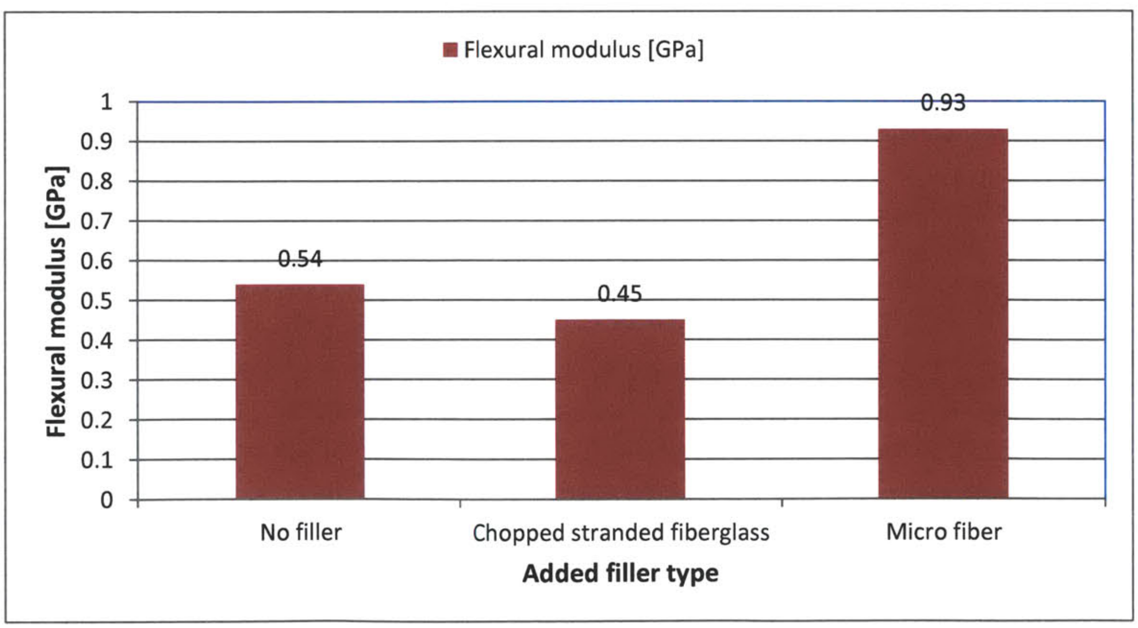


Figure 3-8: Flexural modulus of cork compsoite with different filler type

Influence of facing and comparison with fiberglass samples

The most possible application of the cork composites is being used as a core material inside sandwich panels. In order to see the effects of facing on the composites and their mechanical behaviors as a whole sandwiched structure, E-glass woven fabrics were added onto both sides of the cork composites as a facing material. The GFRP specimens were also tested to compare their mechanical properties. The results were presented in Figure 3-9 and 3-10.

The bending strength and modulus of GFRP specimens were obtained with values of 207.9MPa and 9GPa respectively. The bending strength and modulus of the sandwiched composites showed in Table 4 according to different formulations. It is true that absolute values of mechanical properties of the cork composites are incomparably smaller than those of GFRP specimen, but the density factor could smooth this performance loss when specific properties are considered.

This result also showed the importance of the mechanical properties of core materials on total sandwich panel properties. Even though it is well known that the strength of a sandwich panels come most from high strength of facings, it is clear that core materials mechanical properties plays important role in the sandwich panels for structural strength. In this study, micro fibers gave better adhesion to core and also to the interface between core and facings as already described in previous discussion.

Table 3- 4: Mechanical properties of cork composites with facing

Test series	**Mechanical Properties**				
	Density (Mg/m^3)	Flexural strength (MPa)	Specific flexural strength	Flexural modulus (GPa)	Specific flexural modulus
Pure cork composite (1mm,3mm)	0.63	31.23	49.57	2.55	4.05
Chopped glass strand added composite	0.71	31.84	44.85	2.70	3.80
Micro fibers added composite	0.73	48.69	66.69	4.69	6.42
GFRP	1.36	207.95	152.9	8.92	6.55

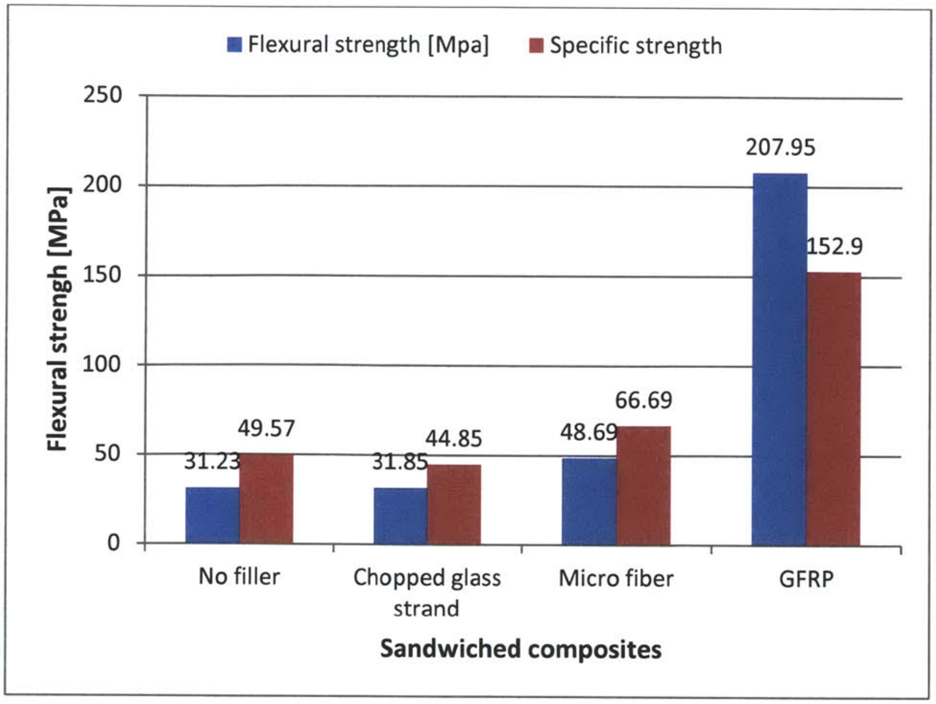


Figure 3-9: Flexural strenght with facing

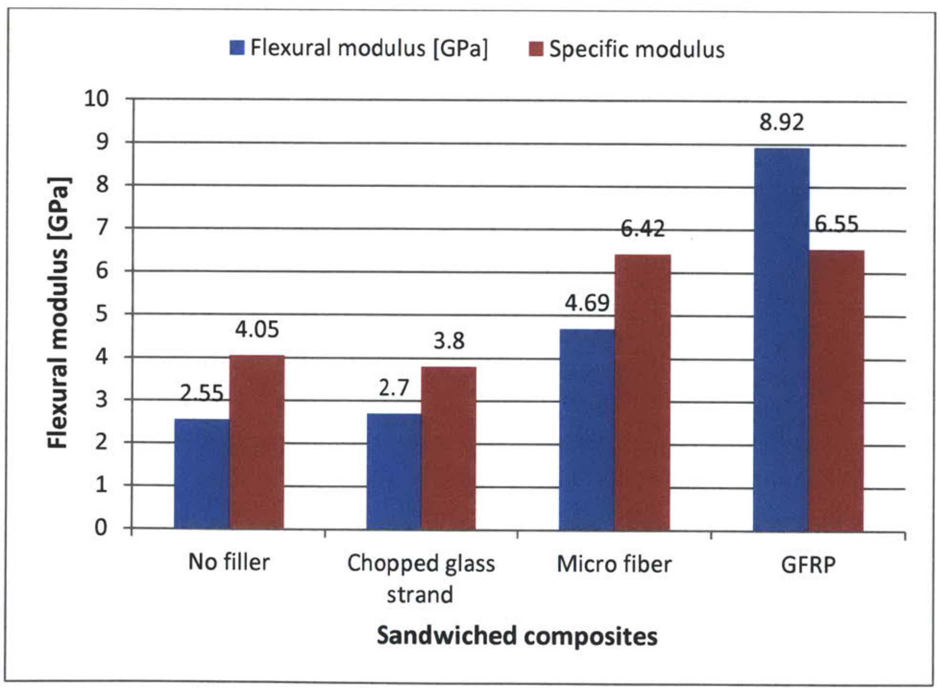


Figure 3-10: Flexural modulus with facing

3.1.2. Tensile test

3.1.2.1. Background theory

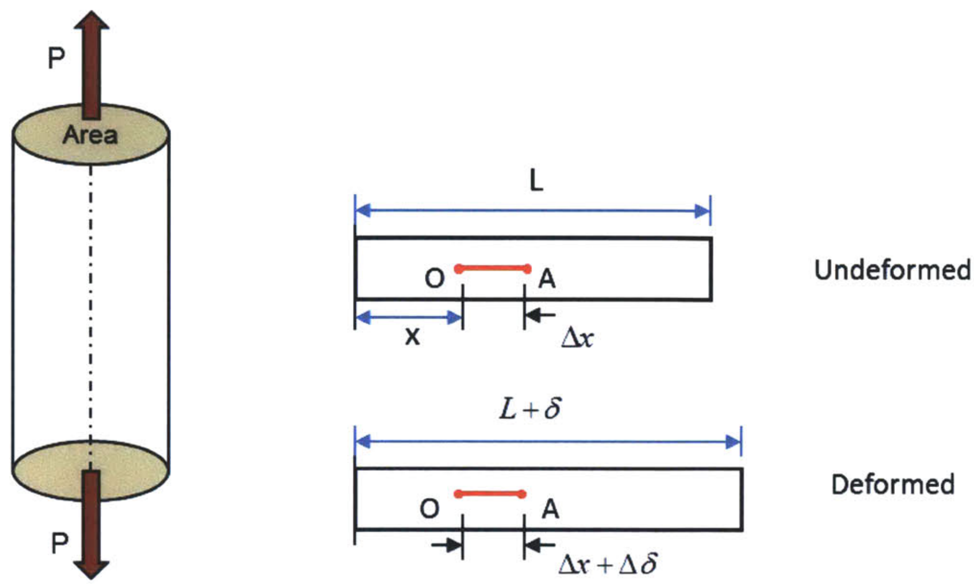


Figure 3-11: Simplified illustration on tensile test

The end of bar carrying normal load of P gives the stress over the cross section A. If the length of bar is longer than 2.5 times of bar's diameter, than the stress over the cross section can be assumed that it is evenly distributed.

$$\sigma = \frac{P}{A} \tag{8}$$

Where

σ= stress over the cross section

P = normal load to the surface

A= area of the cross section

When the elongation δ caused by an applied force is divided by the overall length L, it can be defined as the elongation per unit length, i.e. strain ε.

$$\varepsilon = \frac{\delta}{L} \quad (9)$$

Where

L= length of the bar,

δ = elongation of the bar when a force applied.

Stress σ is proportional to strain as described in equation (10)

$$\sigma = E\varepsilon \quad (10)$$

Where,

E= elastic modulus

ε = strain

If we assume that the stress caused by P is below the proportional limit, then the equation (21) is applicable to calculate the elongation. After plugging equation (8) and (9) into equation (10), the equation (11) for elongation of bar is obtained.

$$\sigma = \frac{\sigma L}{E} = \frac{PL}{EA} \quad (11)$$

Where,

σ= stress over the cross section

P = normal load to the surface

L= length of the bar

E= Elastic modulus

A= area of the cross section

3.1.2.2. Experimental Setup

Testing protocol was based off of the ASTM D638 procedure, which covers the determination of tensile properties of plastics. [13]

<u>Apparatus</u>

For the tensile test, the Instron 5582 is used with a strain rated calculated according to ASTM 638. For the specimen whose thickness is less than 7 mm should be 5 mm/min.

Specimen

For tensile test, there are several types of specimen shapes according to the thickness of the sample. Our composites have less than 7mm thickness. Figure 3-12 shows the experimental setup and specimen for tensile test based on ASTM 638.

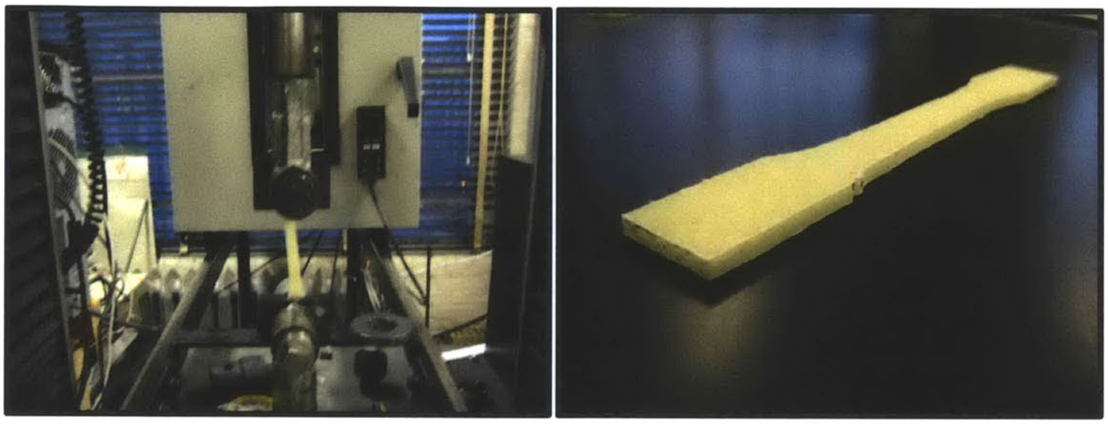


Figure 3-12: Apparatus and specimen for bending test

3.1.2.3. Results and Analysis

Influence of the cork granule size on the mechanical properties

The greatest tensile, strength and modulus were also presented by the combination of 1mm and 3mm cork granules. For tensile tests, also the combinations that contained cork size 1mm tended to have relatively higher properties compared to the combination that excluded the smallest size. Considering that it is common for bending strengths to be greater than tensile strengths for the same materials, and the cork composites have considerable differences between tensile and bending strength, it can be speculated that they have structural defects inside.

Table 3- 5: Mechanical properties of cork composites with different granule size

Test series	Physical and mechanical properties		
	Density (Mg/m^3)	Tensile strength (MPa)	Tensile modulus (GPa)
1,2mm	0.58	4.98	0.18
2,3mm	0.58	4.69	0.16
1,3mm	0.58	5.69	0.19
1,2,3m	0.58	5.23	0.18

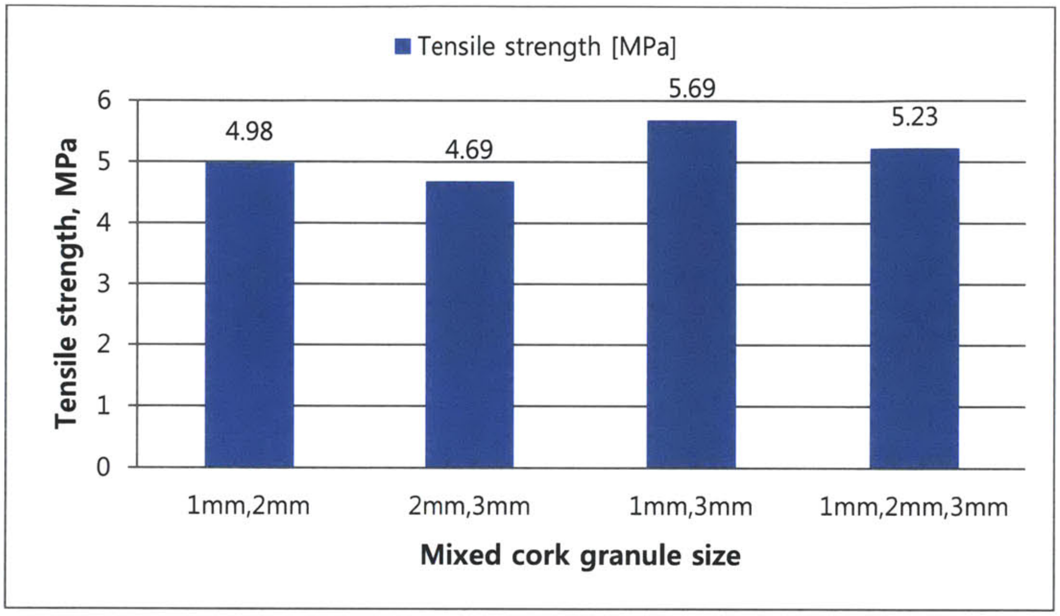


Figure 3-13: Tensile strength of cork compsoite with different granule size

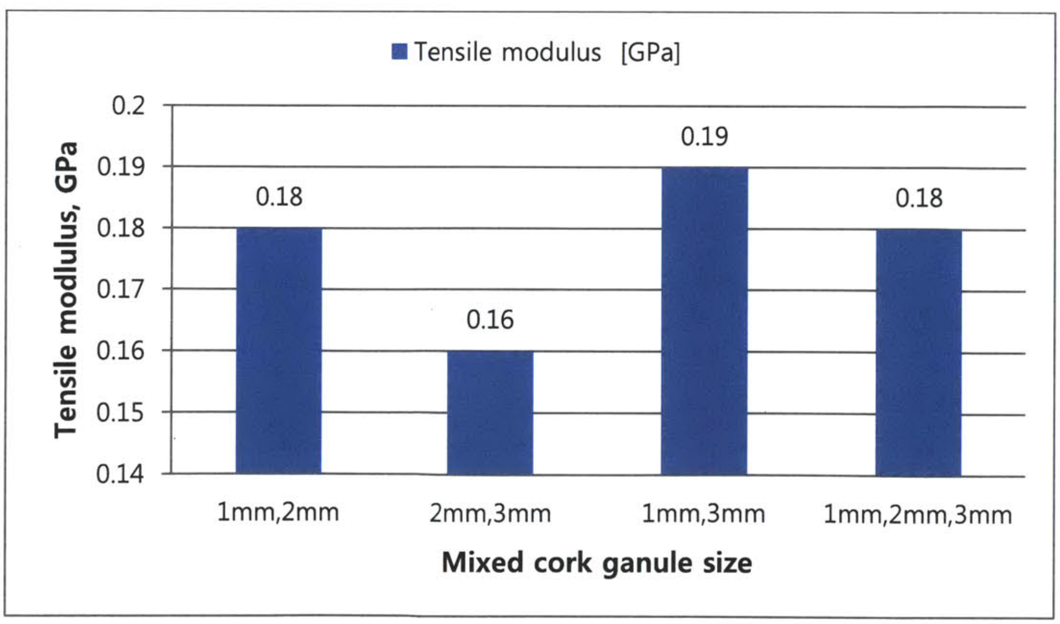


Figure 3-14: Tensile modulus of cork compsoite with different granule size

Influence of additional fillers on the mechanical properties

An interesting thing to look at in the tensile test is that the tensile results of sandwiched cork with long fibers. From bending test results, long fibers don't play an important role to fortify the mechanical properties by adding them into pure cork core. However, for tensile test, the results show that both modulus and strength with long fibers are almost as strong as with short fibers. This is because that the high mechanical property of chopped stranded fiberglass along its lengthwise effectively copes with the force along specimen length.

Table 3- 6: Mechanical properties of cork composites with different filler type

Test series	Physical and mechanical Properties		
	Density (Mg/m^3)	Flexural strength (MPa)	Flexural modulus (GPa)
Pure cork composite (1,3mm)	0.58	5.69	0.19
Chopped glass strand added	0.62	10.5	0.44
Micro fibers added	0.67	10.9	0.48

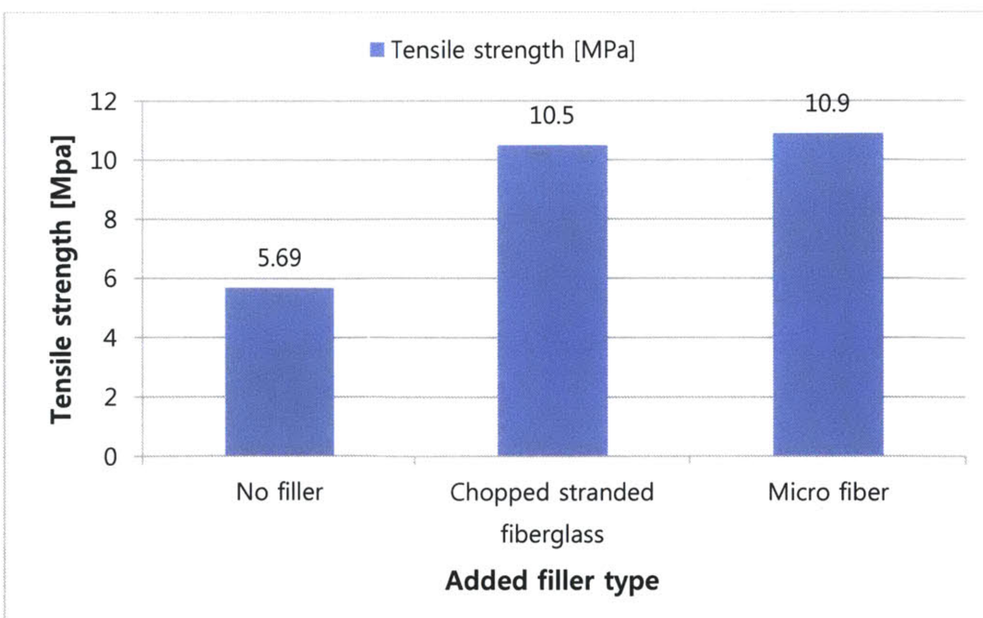


Figure 3-15: Tensile strength of cork compsoite with different filler type

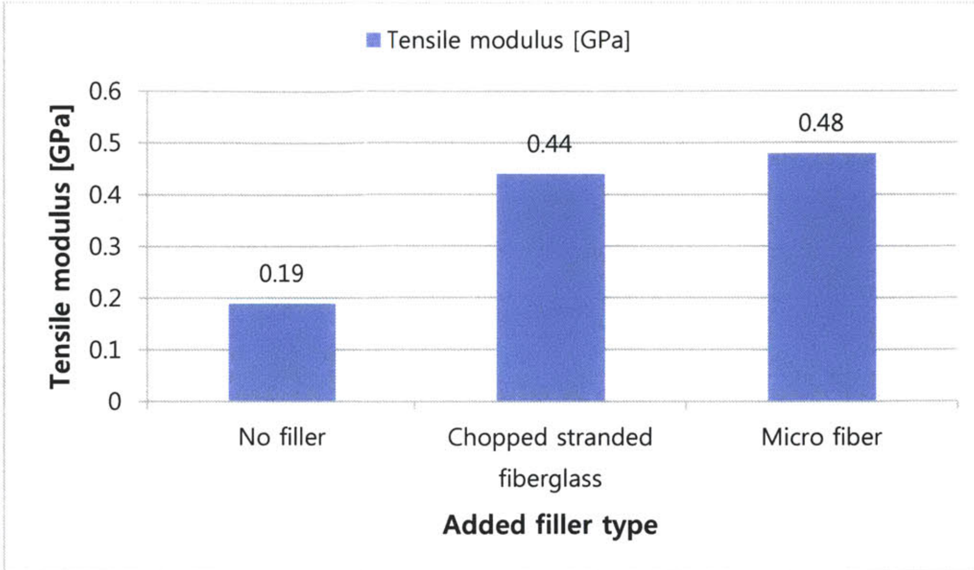


Figure 3-16: Tensile modulus of cork compsoite with different filler type

Influence of facing and comparison with fiberglass samples

When skins are attached to both sides making sandwiched cork, the results shows the different aspects from the bending test: the tensile modulus of sandwiched cork with short fibers is less than flexural modulus but the tensile strength is bigger than flexural strength. One more interesting to look at is the tensile results of sandwiched cork with long fibers. From bending test results, long fibers don't play an important role to fortify the mechanical properties by adding them into pure cork core. However, for tensile test, the results show that both modulus and strength with long fibers are almost as strong as with short fibers.

Table 3- 7: Mechanical properties of cork composites with facing

Test series	Mechanical Properties				
	Density (Mg/m^3)	Tensile strength (MPa)	Specific tensile strength	Tensile modulus (GPa)	Specific tensile modulus
Pure cork composite (1mm,3mm)	0.63	44.2	69.84	1.21	1.91
Chopped glass strand added composite	0.71	92.2	129.85	1.62	2.28
Micro fibers added composite	0.73	57.38	78.60	1.38	1.89
GFRP	1.36	259.79	91.02	5.01	3.68

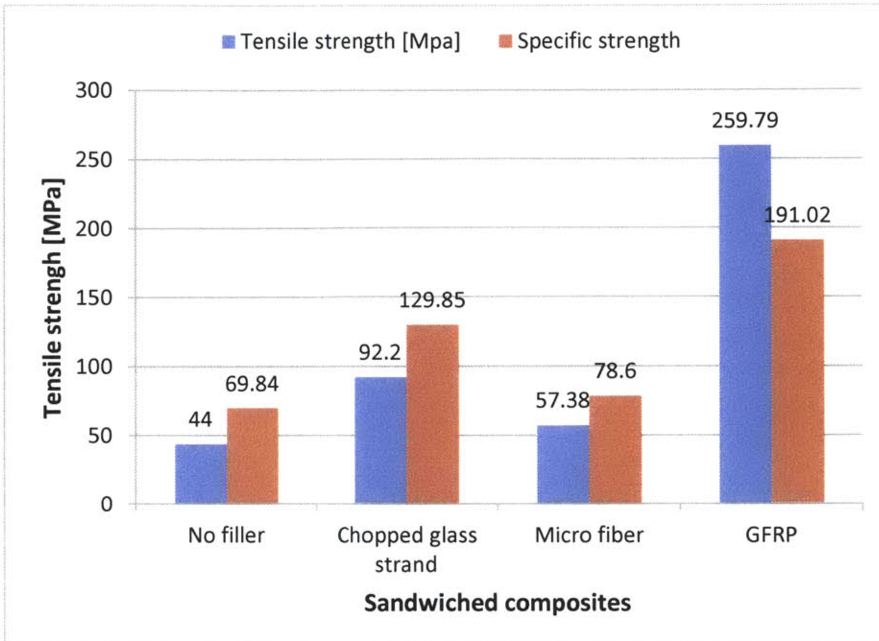


Figure 3-17: Tensile strength and specific strength of cork composites with facing

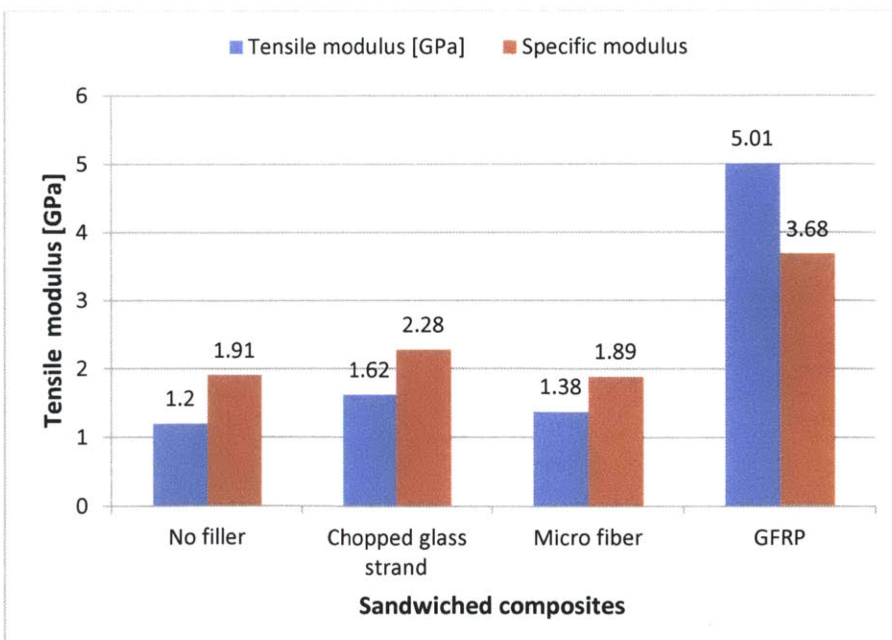


Figure 3-18: Tensile modulus and specific modulus of cork composites with facing

Bending properties vs. tensile properties

The comparison among bending properties and tensile properties are represented in Figure 3.19 in order to see the difference in obtained values.

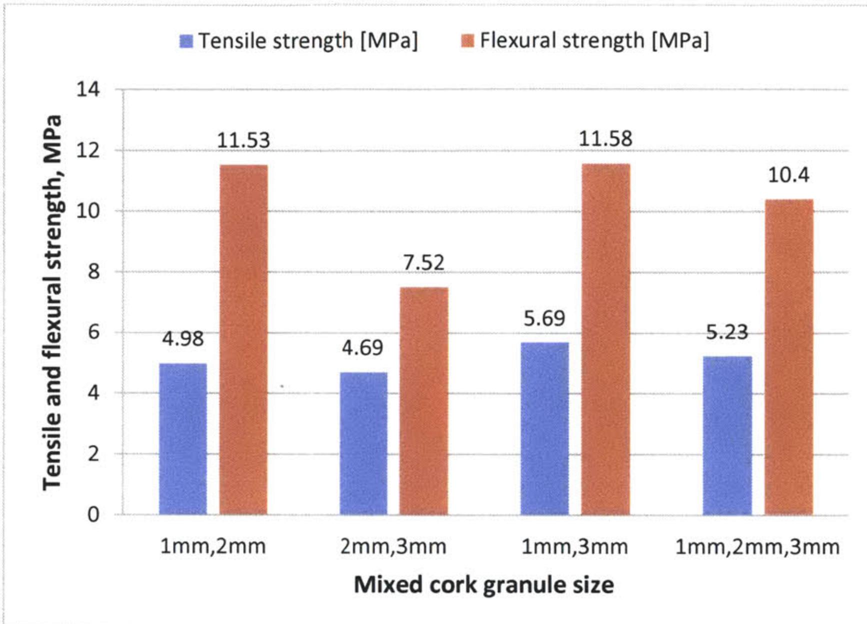


Figure 3-19: Comparison of tensile and fleural strength with different granule size

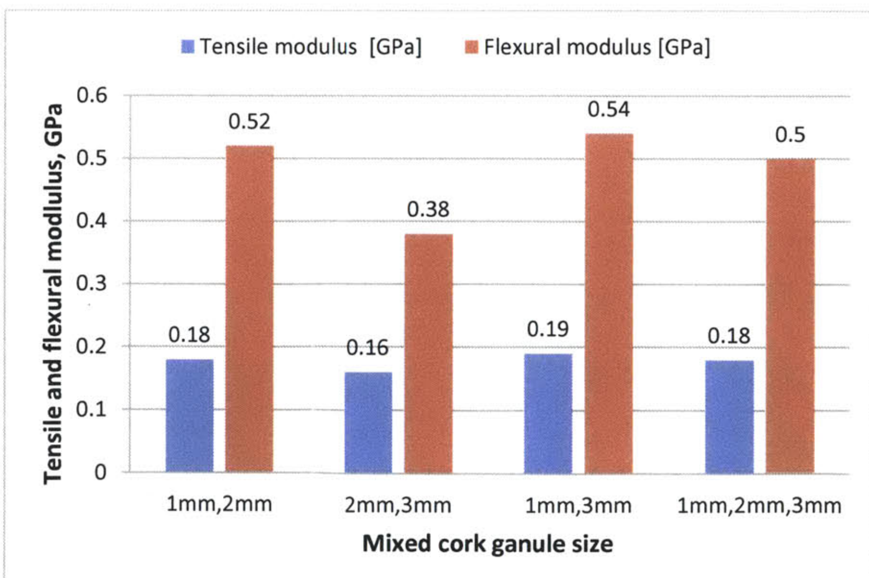


Figure 3-20: Comparison of tensile and fleural modulus with different granule size

When two different types of additional filler added, the results from bending and tensile results are affected by filler type and this is shown on Figure 3-21 and 3-22.

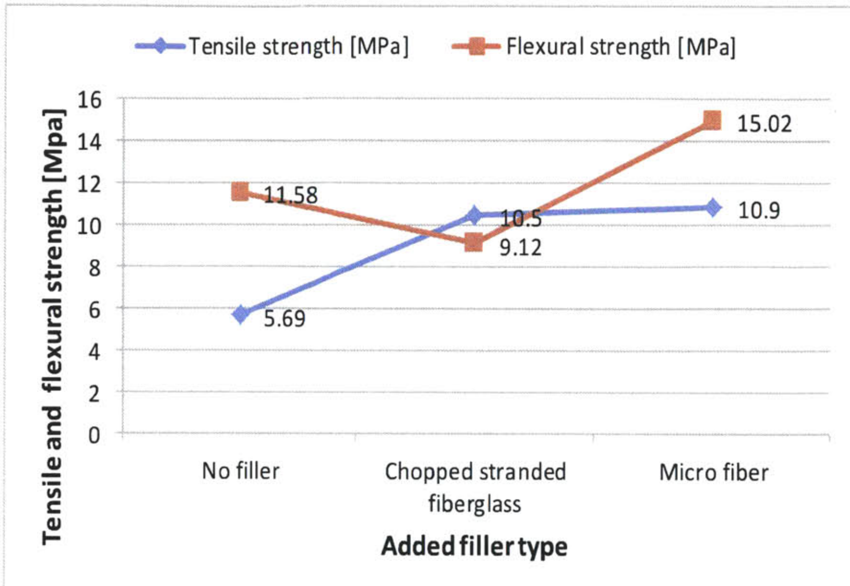


Figure 3-21: Comparison of tensile and fleural modulus with different filler type

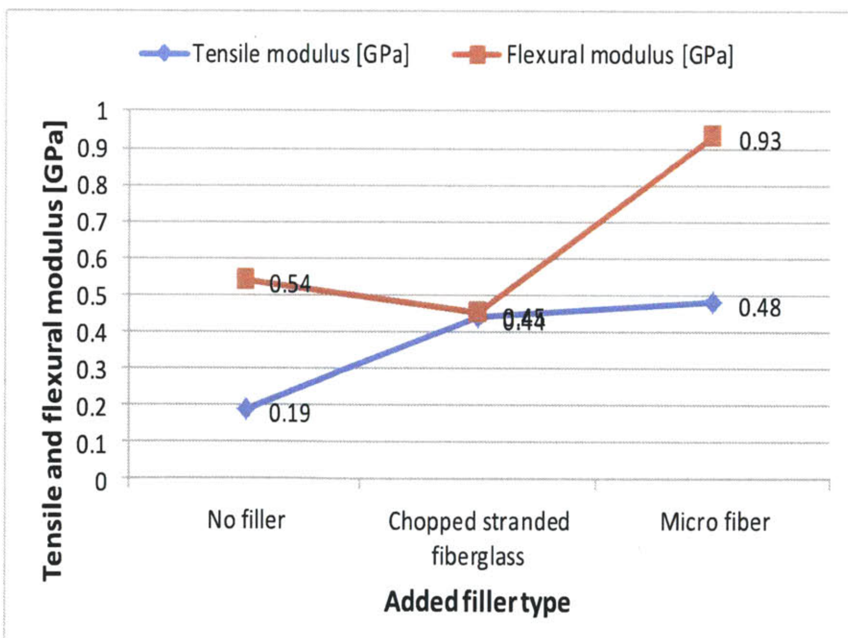


Figure 3-22: Comparison of tensile and fleural modulus with different filler type

The mechanical properties of cork composites can be placed on the density-properties charts to compare with those of other materials.

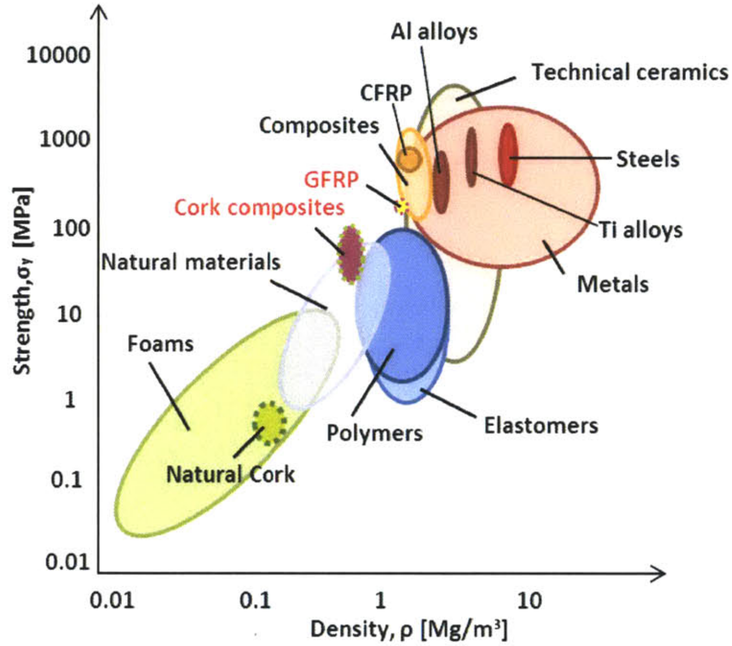


Figure 3-23: The density-strength chart indicating cork composites property

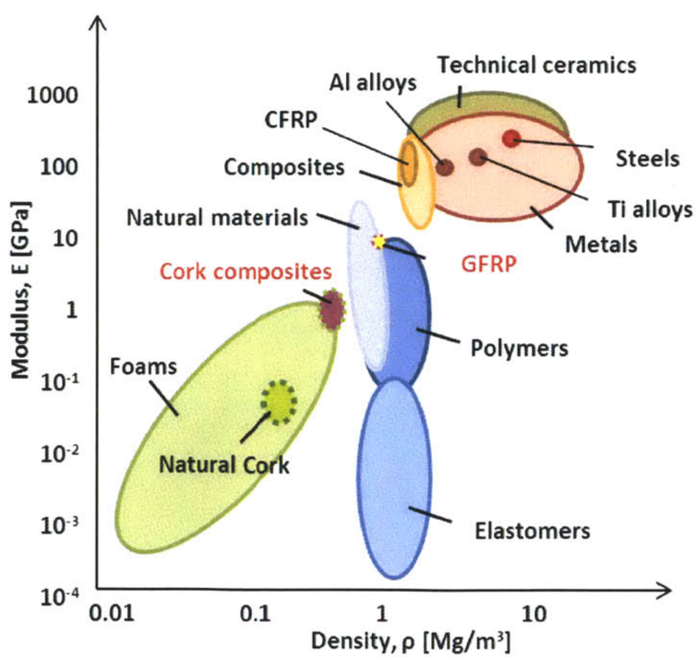


Figure 3-24 : The density-modulus chart indicating cork composites property

3.1.3. Shear test

3.1.3.1. Background theory

This test method consists of subjecting a beam of sandwich construction to a bending moment normal to the plane of a sandwich panel as seen from Figure 3-25. This test method is limited to obtaining the core shear strength, modulus, core-to-facing shear strength and the stiffness of the sandwich panel. Besides this method for measuring shear properties, there are more ways to measure shear properties of materials. Furthermore, there seems to be difference of measured properties between methods. However, the evidence regarding the most appropriate method for determining shear properties is inconclusive.[14]

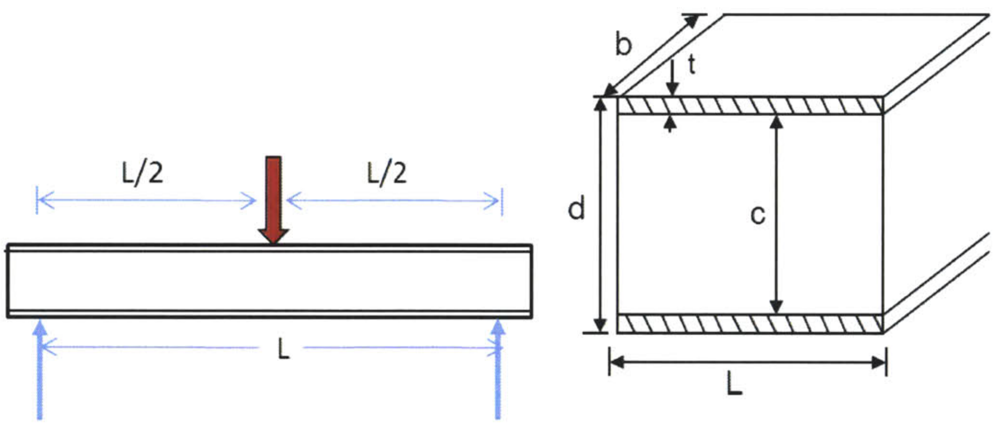


Figure 3-25: Simple illustration for shear testing loading and specimen dimensions

The core shear stress, τ, can be calculated by using the equation (12). P can be maximum loading force prior to failure.

$$\tau = \frac{P}{(d+c)b} \qquad (12)$$

Where

τ = core shear stress, MPa

P = load, N

d = sandwich thickness, mm

c = core thickness, mm

b= sandwich width, mm

The midispan deflection of beam can be separated into two parts: one is due to bending and another is due to shear of the beam. The equation (13) represents this relationship and the basic procedure of getting shear modulus, G, starts from recorded sandwich deflection data from tests.

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4U} \qquad (13)$$

Where

Δ= total beam midspan deflection, mm

P = load, N

L= span length, mm

D = panel bending stiffness, N-mm^2

U= panel shear rigidity, N

Δ is recorded by program simultaneously as tests are conducted and D can be calculated from the equation below, since E, d, c are given values.

$$D = \frac{E(d^3 - c^3)b}{12} \qquad (14)$$

Where

D = panel bending stiffness, N-mm^2

E = facing modulus, MPa

d = sandwich thickness, mm

c = core thickness, mm

b= sandwich width, mm

The only unknown value left in equation (14) is PL/ 4U. Thus U should be calculated by back calculation from equation (13). After getting U, using relationship between U and G as below, the core shear modulus, G can be obtained.

$$U = \frac{G(d+c)^2 b}{4c} \qquad (15)$$

Where

U= panel shear rigidity, N

G =shear modulus, Mpa,

D = panel bending stiffness, N-mm^2

d = sandwich thickness, mm

c = core thickness, mm

b= sandwich width, mm

3.1.3.2. Experimental Setup

Testing protocol was based off of the ASTM C0393 procedure, which covers the determination of the properties of flat sandwich constructions, subjected to flatwise flexure in such a manner that the applied moments produce curvature of the sandwich facing planes.

Apparatus

The Instron 1125, modified by ADMET to include load control, is the test machine with a 20kN loading cell. The suggested speed of testing was set so as to produce failure within 3 to 6 minutes. In this test the speed was set as 6 minutes.

Specimens

The test specimen should be rectangular in cross section. The width should be longer than twice the total thickness, three times the dimension of a core cell, but smaller than one half the span length. The specimen length should be equal to the span length plus 50 mm. Therefore, specimen dimension has the length of 140 mm and the width of 25mm with facings both sides. At least 5 specimens were tested to characterize the property.

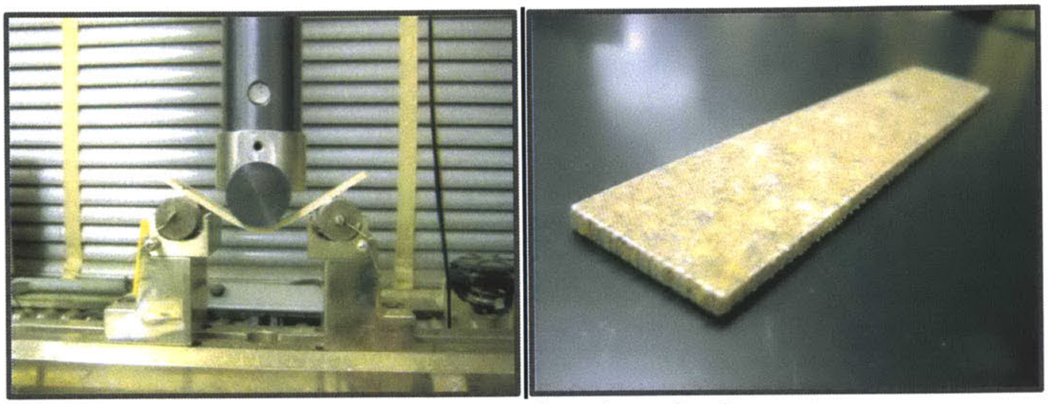


Figure 3-26: A paratus and specimen for shear test

3.1.3.3. Results and Analysis

The evaluation of accurate shear properties of the core material is important in the determination of overall sandwich beam behavior.[15] Shear property of core material is recognized as important since the core shear stiffness has a high degree of influence on the interactions between the constituent components in the sandwich structures. In this study, shear properties of the cork composites inside the E-woven fabric facings are observed. Since two types of filler were suggested to improve the modulus and strength of the cork composites, their effects on shear properties are also investigated. Micro fiber turns out to increase the shear properties of the cork composite more effectively than chapped stranded fiberglass.

Table 3- 8: Mechanical properties of cork composites with different filler type

Test series	Physical and mechanical Properties		
	Density (Mg/m^3)	Shear strength (MPa)	Shear modulus (MPa)
Pure cork composite (1,3mm)	0.58	0.47	4.09
Chopped glass strand added	0.62	0.79	7.83
Micro fibers added	0.67	1.00	12.68

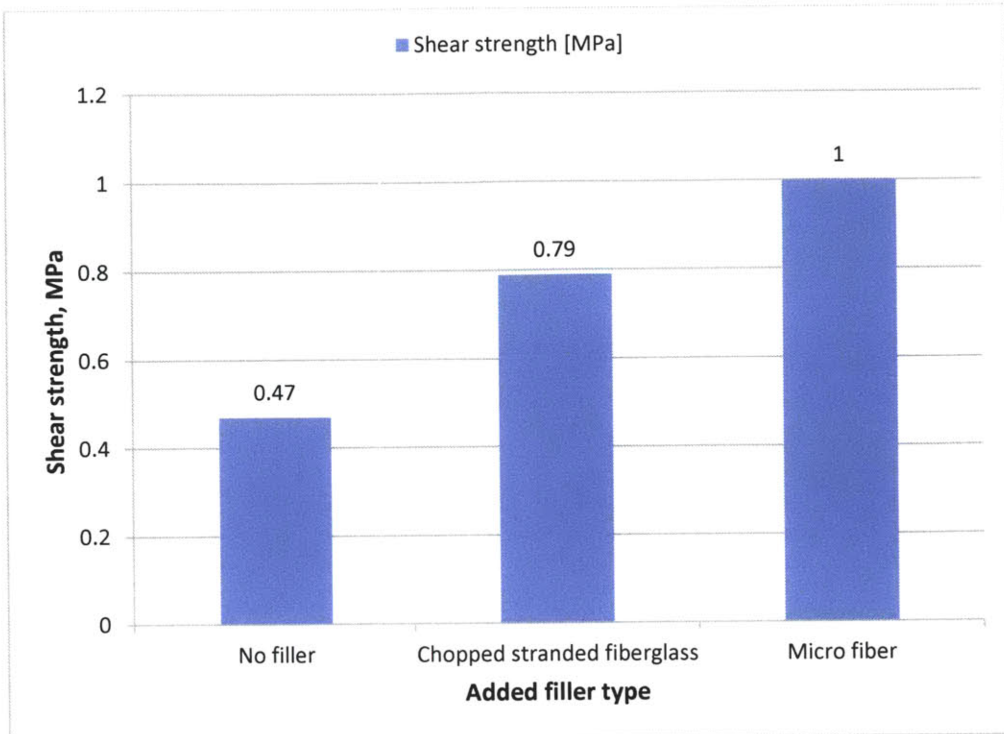


Figure 3-27: Shear strength of the cork composites with different filler tyeps

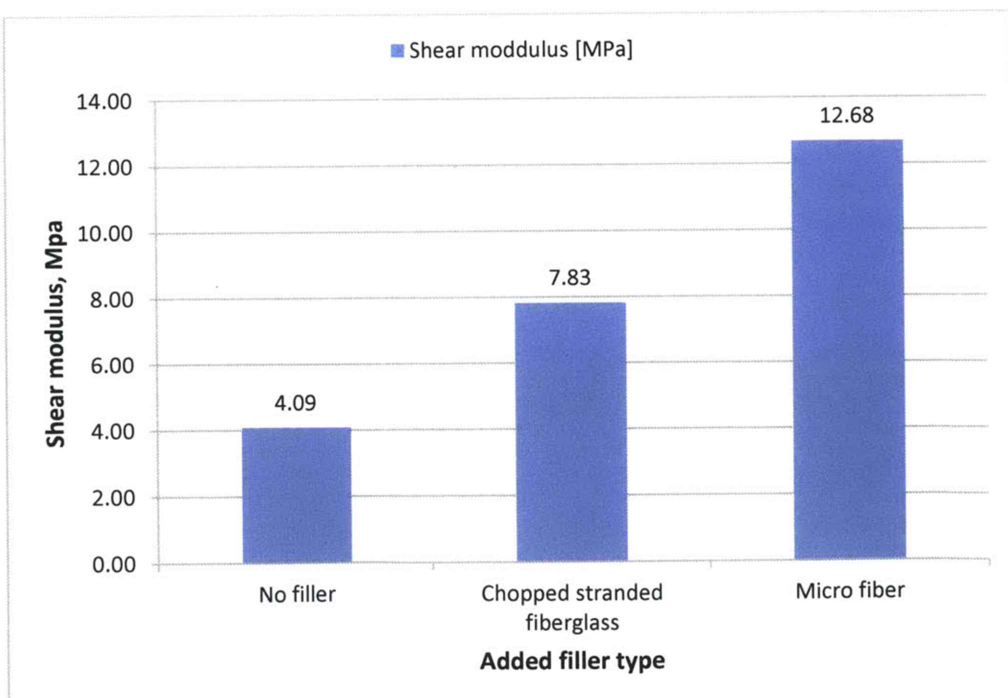


Figure 3-28: Shear modulus of the cork composites with different filler tyeps

3.1.4. Water absorption properties

3.1.4.1. Background theory

Water absorption behavior of a fiber-reinforced composite received considerable attention due to the increase in the usage of the composites for structural applications. The water absorption property of the composites depends on fiber content, temperature, fiber orientation, permeability of fibers, area of the exposed surfaces, void content, hydrophilicity of the individual components etc. [16] The effect of water absorption on the cork composites was investigated by subjecting the composites to an aggressive hygrothermal environment in order to obtain complete or near complete saturation levels. Increased weight is calculated by using equation (16)

$$Increase\ in\ weight,\% = \frac{W-D}{D} \times 100 \qquad (16)$$

Where

W = wet weight

D = dry weight

3.1.4.2. Experimental setup

Testing protocol was based off of the ASTM C272, which covers the determination of the relative amount of water absorption by various types of structural core materials when immersed or in a high relative humidity environment. Before immersion, specimens are dried in the oven for 2 hours at 105°C and weighed. After being immersed in deionized water at room temperature 20°C for 1day, the percentages increase in weight are calculated. [17]

<u>Specimens</u>

The test specimen should be 75 by 75 by 12.7 mm thick.

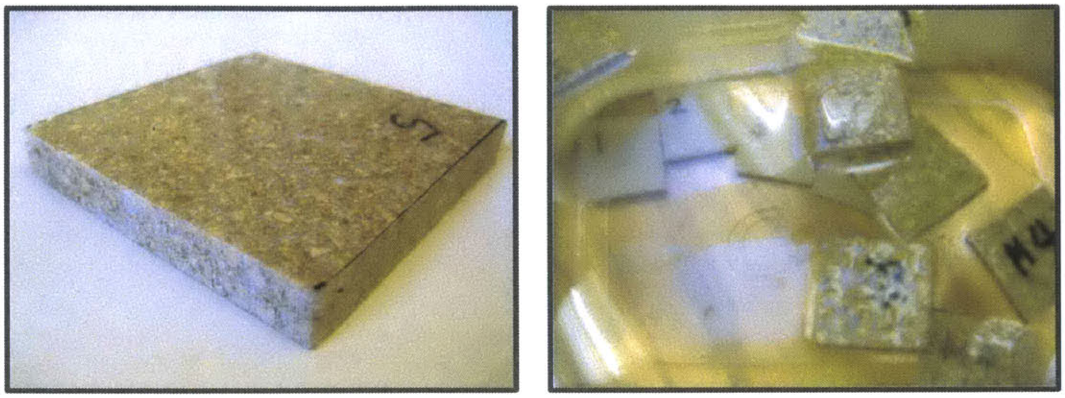


Figure 3-29: A specimen for water absorption test

3.1.4.3. Results and Analysis

Moisture uptake was quantified for each of the composites with and without added micro fiber. Non micro fiber added composite had a moisture uptake 1.93% and added composites had less water uptake as the filler volume ratio increased. From the result, it is clear that as the filler volume ratio increased the water absorption decreased. Because of the three dimensionally cross-linked networks the cured epoxy resin shows low water absorption.

Table 3-9: Increase in weight of the cork composites after water absorption test

Test series	**Increase in weight after water absorption tests**	
	Density (Mg/m^3)	Compressive modulus (MPa)
0	0.58	1.93
1/4	0.61	1.82
1/3	0.63	1.63
1/2	0.63	1.49

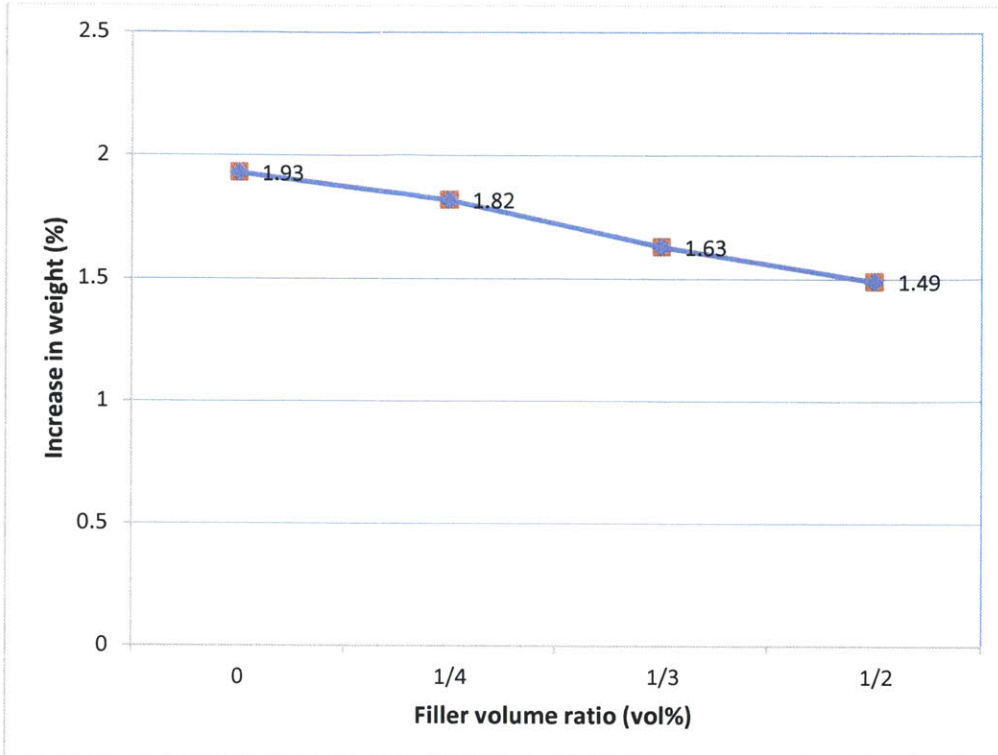


Figure 3-30: Increase in weight of the cork composite after being exposed to moisture as a function of filler volume ratio.

3.15. Compressive property

3.1.5.1. Background theory

The compressive strength and modulus are fundamental properties for core materials that are used in design of sandwich panels. This test method described here covers the determination of the compressive strength and modulus of sandwich cores. These properties are usually determined for design purposes in a direction normal to the plane of facings as the core would be placed in a structural sandwich construction

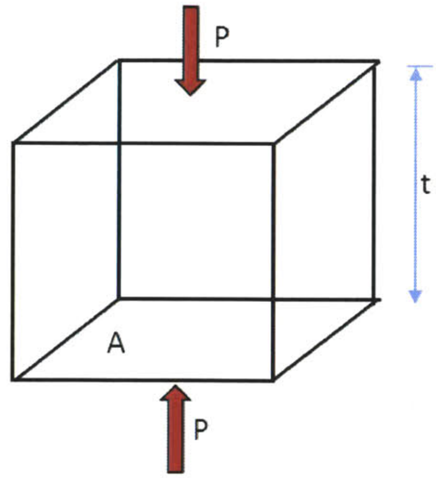


Figure 3-31: Simple illustratio for compression test

$$\sigma = \frac{P}{A} \qquad (17)$$

Where

σ = core compressive strength, MPa

P = ultimate load, N

A = cross-sectional area, mm^2

The flatwise compressive modulus is calculated as follows

$$E = \frac{St}{A} \qquad (18)$$

Where

E = core compressive modulus, MPa

S = (ΔP/Δu) slope of initial linear portion of load-deflection curve, N/mm

u = displacement of the loading block

t = core thickness, mm

3.1.5.2. Experimental setup

Testing protocol was based off of the ASTM C365 procedure, which covers the determination of the compressive strength and modulus of sandwich core. [18]

Apparatus

The Instron 5582 is used with recommended loading rate at 0.5 mm/min.

Specimens

The test specimen should be core of sandwich panels and shall be square or circular cross section. Since the cork composites are a continuous core such as balsa wood and foams, the minimum cross section should be 625 mm^2. At least 5 specimens are tested to characterize the property.

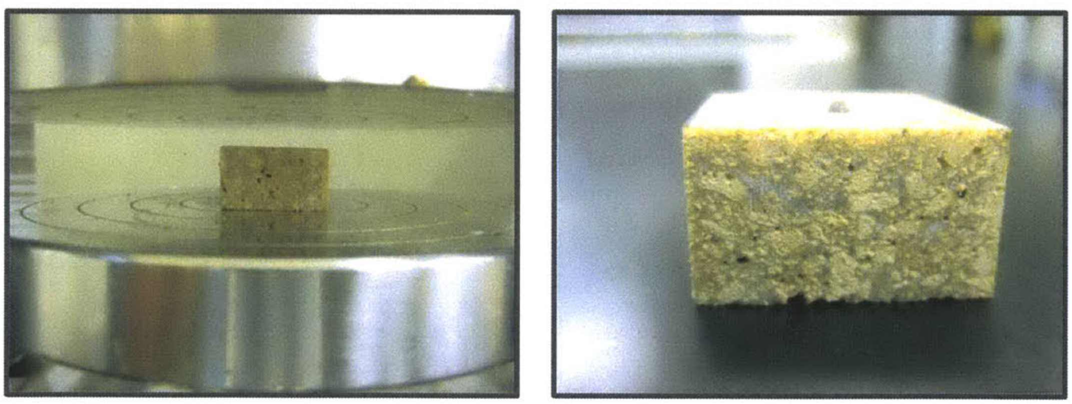


Figure 3-32: A paratus and specimen for compression test

3.1.5.3. Results and Analysis

Compressive properties before/after water absorption

The compressive modulus and strength of the cork composites, before and after water immersion, was determined in accordance with ASTM 365. From this compression tests, two interesting results were obtained. The maximum strength was obtained from the cork composite that has the filler volume ratio 1/3. This means that even adhesive filler improves the mechanical properties, its amount should not exceed the cork amount. Another interesting thing is that more filler was added, the decreased ratio of compressive modulus and strength were smaller. Figure 3-33, 3-34 show the compression properties for the different filler volume ratio before after hygrothermal exposure, illustrating the decrease in mechanical properties with water absorption. When filler and cork amounts are the same in the constituents, the compressive strength only decreased 5% after exposure to excessive moist and modulus didn't change. However, the pure cork composite that doesn't have adhesive fiber inside has 27% of decreased compressive strength and 33% of decreased modulus. When the cork composite doesn't have micro fiber inside, water molecule can penetrate the composite and reach cork easily, causing swelling of the cork. As the cork and the epoxy do not expand at the same rate, micro-cracking will occur in the matrix around cork, which leads to decrease in mechanical properties.

Table 3-10: Compressive properties before/ after exposure to moisture

Filler volume ratio **Exposure to water**	**0** **before/after**	**¼** **before/after**	**1/3** **before/after**	**1/2** **before/after**
Compressive strength (MPa)	7.8/5.7	9.3/7.2	13.3/11.6	10.3/9.8
Compressive modulus (GPa)	0.18/0.12	0.24/0.2	0.34/0.31	0.32/0.32

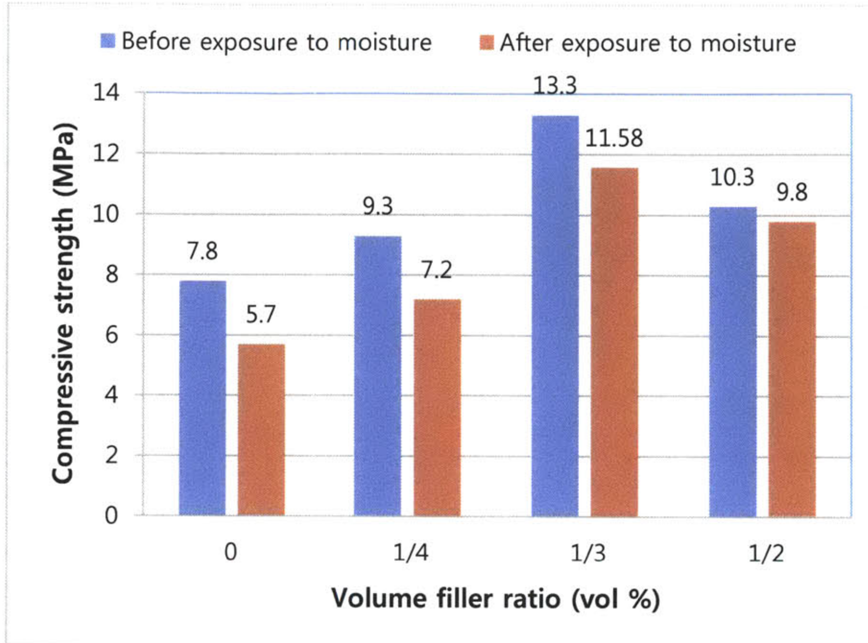


Figure 3-33: Compressive strength of cork composites as a function of filler volume ratio before/after exposure to moisture

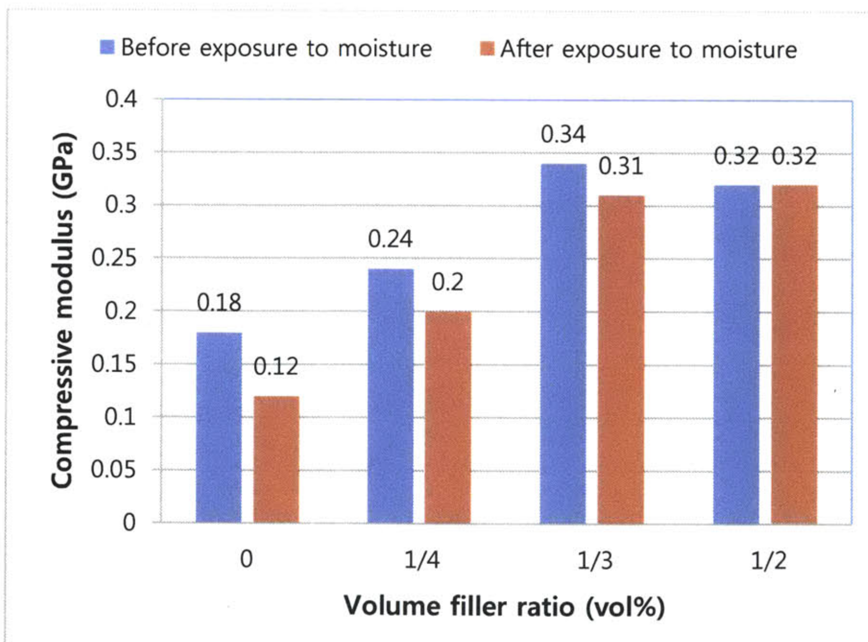


Figure 3-34: Compressive modulus of cork composites as a function of filler volume ratio before/after exposure to moisture

3.1.6. Fracture toughness property

3.1.6.1. Background theory

Toughness is the resistance of a material to the propagation of a crack. [4] When the tensile force is applied to materials that contains a small, sharp crack as seen from Figure 3-35, a tough material will yield, work harden and absorb energy as before in (b), while brittle material has a sudden crack propagation in (c).

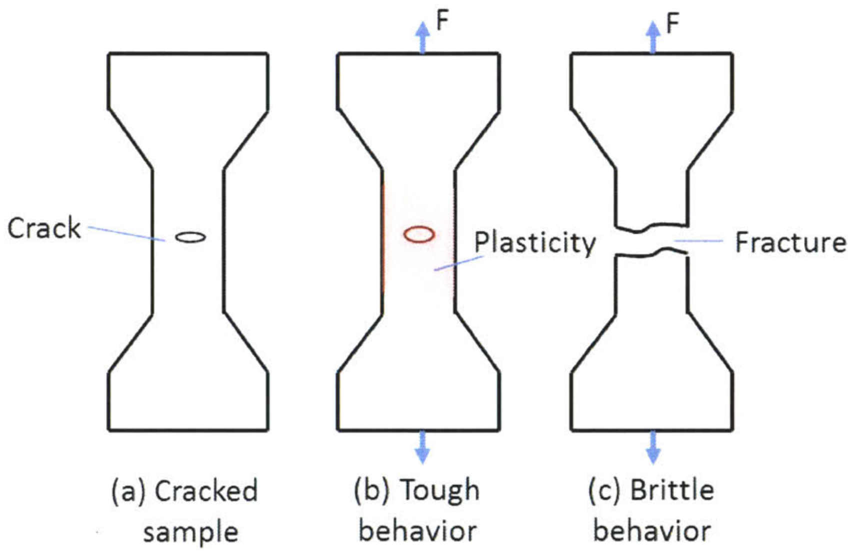


Figure 3-35: Tough and brittle behavior of a material

Cracks concentrate stress. The force generated by remote stress σ is transmitted through a material that contains crack as in Figure 3-36. The local stress, σ_{local}, is non-uniform, and rising steeply at crack tip. It is proportional to the number of lines of force crossing unit length of cross-section. It can be assumed that the crack radius at the tip is essentially zero.

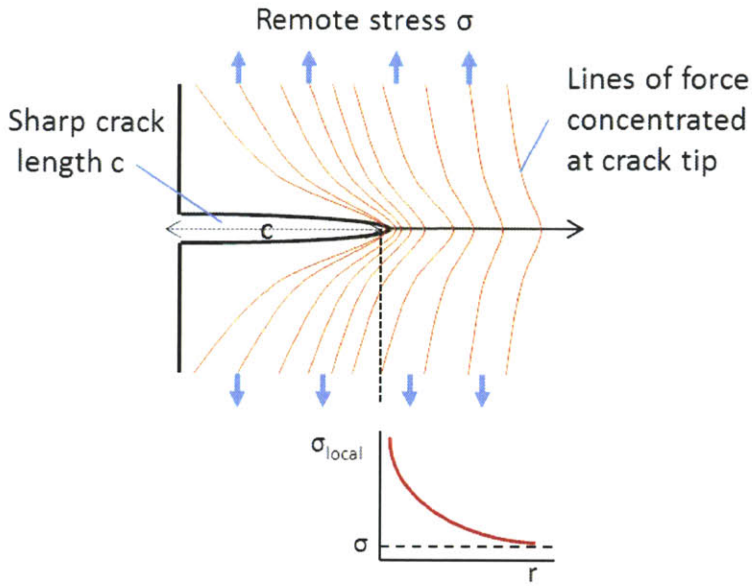


Figure 3-36: Lines of force in a cracked body under load [4]

The local stress at distance r from its tip caused by a remote uniform tensile stress, σ is defined as in equation (19).

$$\sigma_{local} = \sigma(1 + Y\sqrt{\frac{\pi c}{2\pi r}}) \qquad (19)$$

Where

σ = Tensile stress, MPa

Y = a constant with a value near unity

c = crack length, mm

r = distance from its tip, mm

When c « r, local stress, σ_{local}, falls to the value σ, but near the tip, where c » r, the stress rises sharply reaching to the value in equation (20).

$$\sigma_{local} = \sigma Y\sqrt{\frac{\pi c}{2\pi r}} \qquad (20)$$

Where

σ = Tensile stress, MPa

Y = a constant with a value near unity

c = crack length, mm

r = distance from its tip, mm

Therefore, for any given r, the intensity of the local stress is $\sigma\sqrt{\pi c}$ this quantity is called the mode 1 stress intensity factor and defined as below.

$$K_{1c} = Y\sigma\sqrt{\pi c} \qquad (21)$$

This intensity factor is also interpreted as a critical value over which the crack propagates. Thus, this critical value is called fracture toughness and this is a material property independent of the way it measures. It is very hard to build a structure that is completely without any cracks. Therefore, it is important to design material that can resist against well crack propagation. Therefore, fracture toughness test is conducted on the cork composite to see their abilities to carry a given load without failure due to preexisting cracks.

There are many specimen configurations associated getting K_{1c}. In this study, a cracked beam with central load force was chosen to see the fracture toughness property of the cork composite.

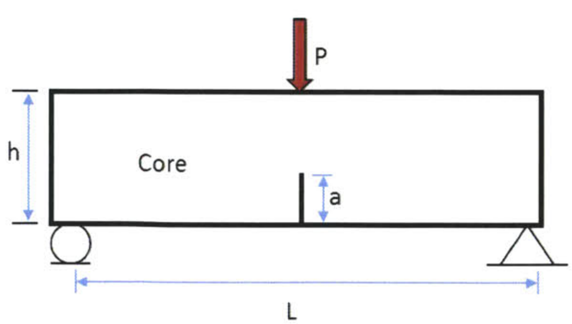


Figure 3-37: An illustration for representing loading condition to get K_{1c}

$$K_{IC} = \frac{6P_C}{h}\sqrt{\pi a}F(\frac{a}{h}) \tag{22}$$

Where

P_c = critical load, N

a = crack depth, mm

h = core thickness

F(a/h) is defined as in equation ()

$$F(\frac{a}{h}) = \frac{1}{\sqrt{\pi\pi}} \frac{1.99 - \frac{a}{h}(1-\frac{a}{h})(2.15 - 3.93\frac{a}{h} + 2.7(\frac{a}{h})^2)}{(1+2\frac{a}{h})(1-\frac{a}{h})^{3/2}} \sqrt{\pi a} \tag{23}$$

Where

a = crack depth, mm

h = core thickness

3.1.6.2. Experimental setup

Testing protocol was based off of the ASTM D5045 procedure, which are designed to characterize the toughness of plastics in terms of the critical-stress-intensity factor, K_{1c}. The single-edge-notch bending (SENB) was adopted to characterize K_{1c}. [19]

Apparatus

The Instron 1125, modified by ADMET to include load control, is the test machine with a 20kN loading cell. The loading rate of 10mm/min was used.

Specimens

Specimen dimensions are shown in Figure 3-39. The crack should be sharp enough to ensure that the minimum value of toughness is obtained. The specimen thickness B should be identical if the material is supplied in the form of a sheet. The sample width, W, is $W = 2B$. Since the crack length, a, should be selected such that $0.45 < a/W < 0.55$, it is selected as 0.5B for the cork composites.

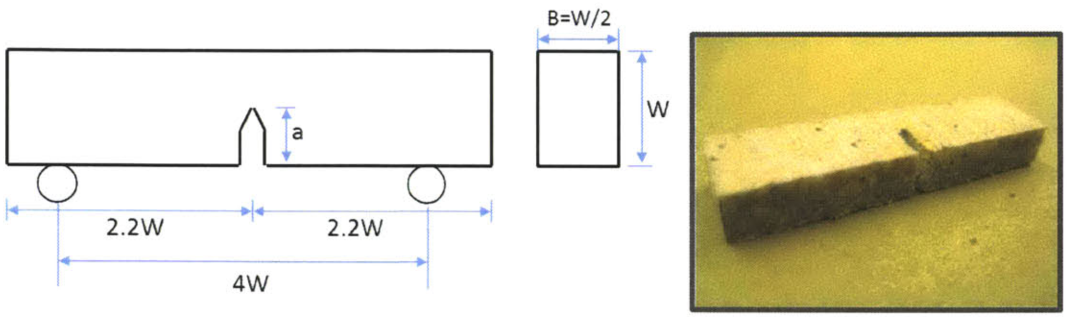


Figure 3-38: Specimen dimensions for fracture toughness test

3.1.6.3. Results and Analysis

For structural materials that have natural or artificial defects such as knots, machined notches and holes, fracture toughness is important since those defects can become stress raiser within the material. The nature and influence of such stress raisers on the stress and strains in their vicinity has been the focus of fracture mechanics. In this study, single edge notch bend (SENB) tests were conducted to study the mode-I fracture behavior of cork-based composites. The stress intensity factor K_{IC} was calculated from the loading curves

Most thermoset plastics show the linear-elastic relationship in tension. The fracture failure can thus be treated by the concept of linear-elastic fracture mechanisms. [4] Since the cork composites are particulate composites so there is a high possibility that it contains defects inherently when they are fabricated. Therefore it is worthy to observe the resistance of cork-based composite against the propagation of pre-existed crack.

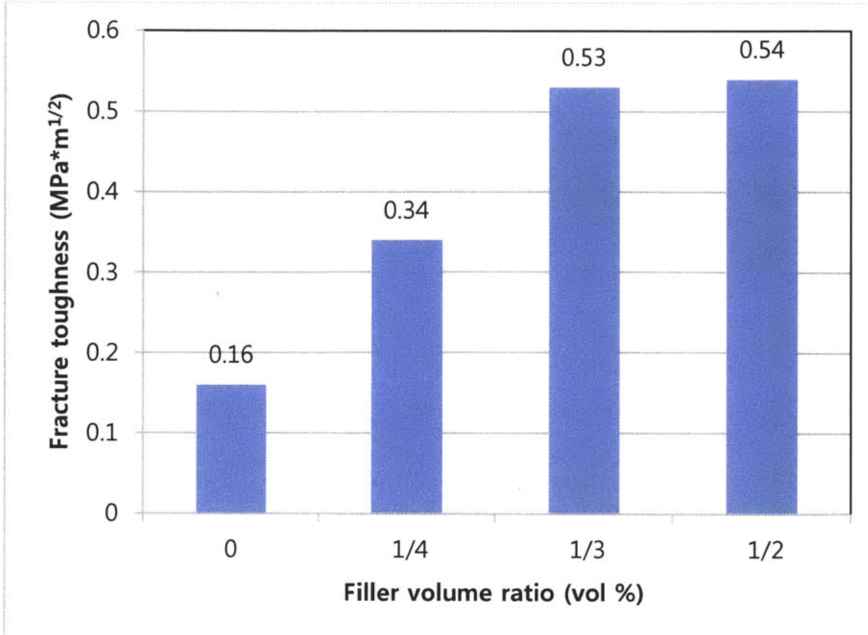


Figure 3-39: Fracture toughness results of the cork composites as a function of filler volume ratio

Table 3-11: Fracture toughness results

Test series	Increase in weight after water absorption tests	
	Density (Mg/m^3)	K_{1c} ($MPa.m^{1/2}$)
0	0.58	0.16
1/4	0.61	0.34
1/3	0.63	0.53
1/2	0.63	0.54

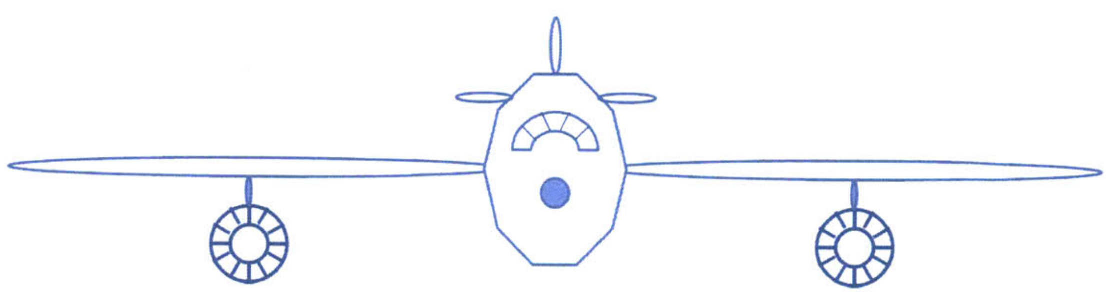
As already observed, adhesive filler helps the cork composite to have high internal bonding giving high fracture toughness value. Adhesive filler became sticky and fluidic when mixed with epoxy resin since it is a silicon dioxide cotton flock and decreases and coats the gaps between cork granules effectively. Micro-cracking inside the cork granules can be delayed by increasing the volume filler ratio. As different with the impact strength results, the fracture toughness increases as filler volume ratio increases. More cork granules provide more defects when they are cured into the epoxy matrix.

3.2. Design

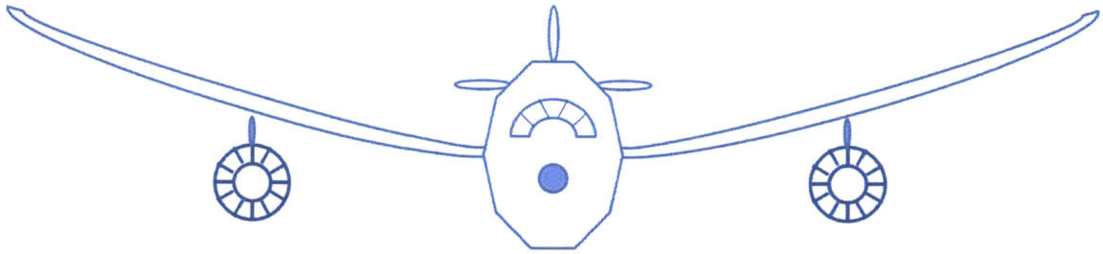
3.2.1. Objective

Finite element and computer aided design methods are normally used for sandwich structures in aerospace applications to examine details of the stress distribution through the core and skins of the structure in terms of the applied loads. However, these detailed analysis methods are not appropriate for checking up some criteria for aimed applications under limited material properties. Therefore, a simpler design approach needs to be used in which the several material properties should be independently considered for applications.

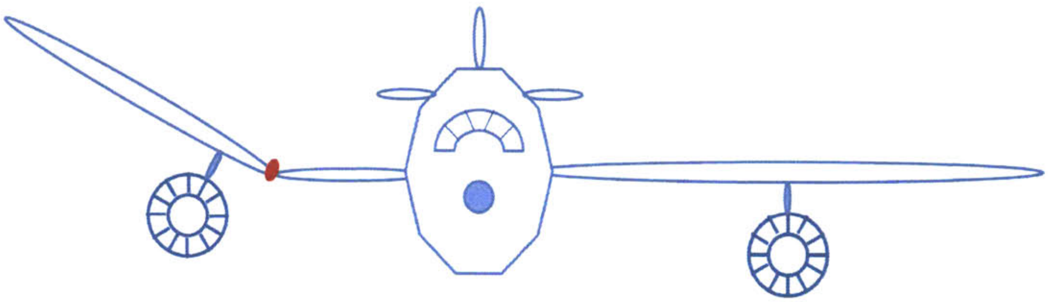
For example, a steel ruler is easy to bend elastically. Its resistance to bending, bending stiffness, is partially determined by its elastic modulus E. In Figure 3-40 (b) illustrates the consequences of inadequate stiffness. If we want to give a permanent deformation to the ruler, it should experiences strength beyond its yield strength, σ_Y. Lower σ_Y it has, easier it can be bent. Figure 3-40 (c) illustrates the consequences of inadequate yield strength. The resistance of materials to cracking and fracture is measured by fracture toughness, K1c. and too low K1c allows a sudden fracture of materials without warning. Figure 3-40 (d) illustrates this situation conceptually.[4]



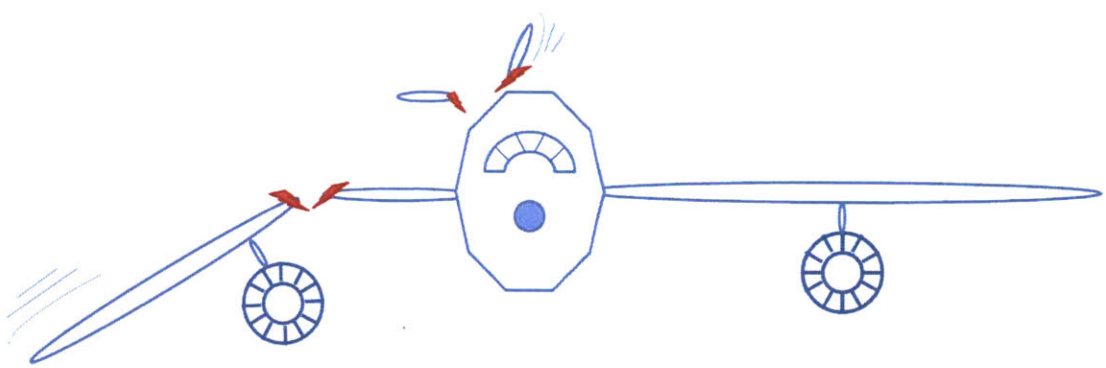
(a) Normal



(b) Not stiff enough (E too low)



(c) Not strong enough (σ_Y too low)



(d) Not tough enough (K_{1C} too low)

Figure 3-40: Mechanical properties for meeting design requirements [4]

Mechanical properties of cork composite are obtained by mechanical tests done in the previous chapter, but it is not easy to see their relative competitiveness with other core materials simply because only absolute values representing each mechanical property were determined. Therefore, the process that compares excellence of each core material under the limitation of specific properties for design of chosen application is needed. In this chapter, stiffness, strength, and fracture limited design cases for a panel are overviewed to see the possibility of the cork composites as a structural material.

3.2.2. Stiffness-limited design

A panel is a flat, like a table top. Its length L and width b can be specified but its thickness h is free to set. Figure 3-42 represent a panel loaded in bending. Central load F is loading in bending. The stiffness-limited design requires that the deflection of panel should not exceed δ under the load F. The objective is to make the panel as light as possible under this constraints. Table 3-12 summarizes the design requirements for the light stiff panel.

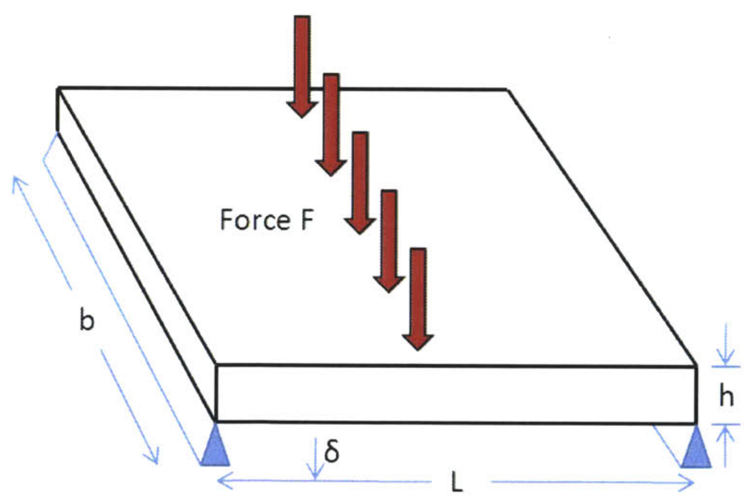


Figure 3-41: Panel loaded in bending with dimension

Table 3-12: Stiffness-limited design requirements for the light stiff panel

Function	Panel in bending	
Constraints	Stiffness S* specified	Functional constraint
	Length L and width b specified	Geometric constraint
Objective	Minimize the mass m of the panel	
Free variables	Choice of material	
	Choice of panel thickness h	

3.2.2.1. Background theory

The objective function is to minimize the mass of the panel.

$$m = AL\rho = bhL\rho \quad (24)$$

Where

m = mass of the panel, kg

b = depth of the panel, m

h = thickness of the panel, m

L= length of the panel, m

ρ = density of panel, kg/m^3

The bending stiffness S is given as:

$$S = \frac{C_1 EI}{L^3} \quad (25)$$

Where

S = bending stiff ness

C_1 = constant

E = Young's modulus, GPa

I= second moment of area of panel, m^4

L= length of the panel, m

The second moment of area of beam for a rectangular section is

$$I = \frac{bh^3}{12} \quad (26)$$

Where

I= second moment of area of panel, m^4

b = depth of the panel, m

h = thickness of the panel, m

The stiffness S*, the length L and the width b are specified; only the thickness h is free variable. The mass can be reduced by reducing h, but still the stiffness constraint is met. By equating equation (25) and equation (26), the objective function becomes

$$m = \left(\frac{12S}{C_1 b}\right)^{1/3}(bL^2)\left(\frac{\rho}{E^{1/3}}\right) \qquad (27)$$

Since the quantity S*, L, b and C_1 are all specified, the only free quantity that can vary is E and ρ of material. The best material for a light, stiff panel is those with the largest values of $E^{1/3}/\rho$. [5] .Let's call this $E^{1/3}/\rho$ index M. This M can be plotted in the material density-modulus chart as a line with a slope of 3 by taking logs.

$$M = \frac{E^{1/3}}{\rho} \qquad (28)$$

Where

M= index

E = Young's modulus, GPa

ρ = density of panel, kg/m^3

By taking logs, equation (28) becomes equation (29). This equation can be plotted as straight lines on density- modulus charts in Figure 3-43.

$$\log(E) = 3\log(\rho) + 3\log(C) \qquad (29)$$

3.2.2.2. Results and analysis

If a material is deformed elastically, it goes back to its original shape when applied force is removed. This can be thought as little springs inside materials. If the springs are hard to stretch, the material is stiff; they are easy to stretch, the material is compliant. Young's modulus is a measure of the stiffness or compliance of the materials. The density-modulus chart shows the relationship between modulus and density of materials. By examining the stiffness-limited design, we could see that what materials perform better than others considering their weight and stiffness synthetically and now it is relatively easy to read off the performance of each material in the form of a panel since all the materials that line on a line of constant M= $E^{1/3}/\rho$ performs equally. A material that has M =3 can have 1/3 of weight of one with M =0.3. The cork composites have value of 1.7-2.3 which is higher than those of GFRP. This result approves that the cork composites are competitive for panel applications.

Table 3-13: Index value of cork composites and GFRP

	Density ρ (Mg/ m^3)	Modulus E (GPa)	Index M
Cork composites	0.58-0.73	0.5-4.7	1.7-2.3
GFRP	1.36	8.92	1.52

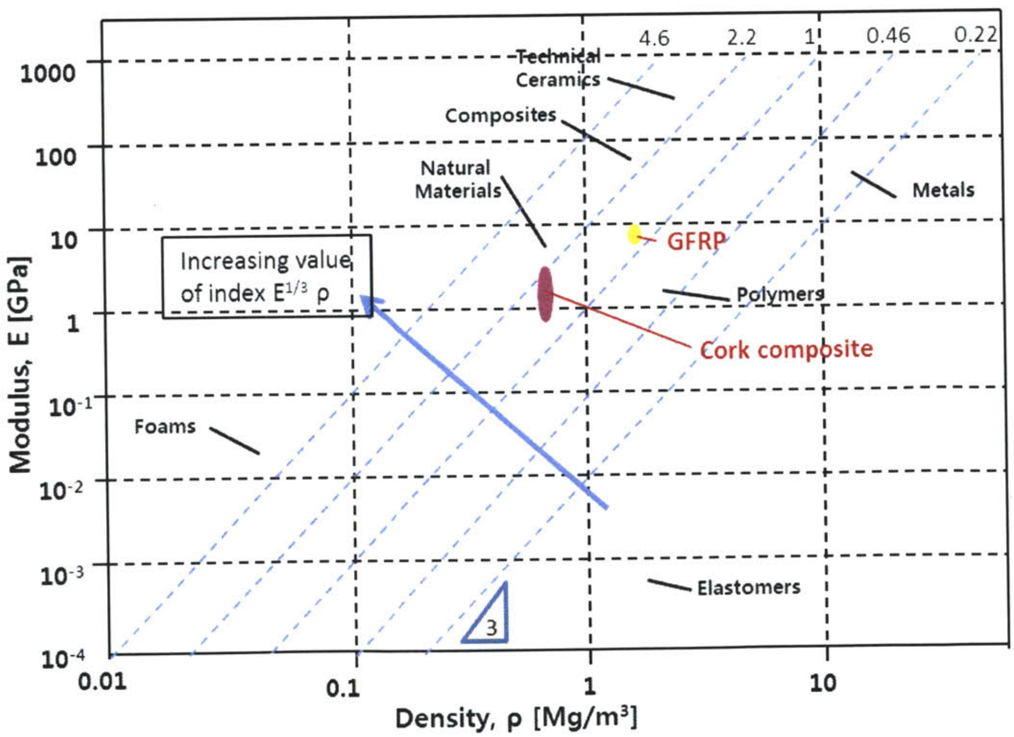


Figure 3-42: A schematic density-modulus chart showing guidance for light, stiff panel

3.2.3. Yield-limited design

The objective for yield- limited design is also to minimize the mass of the panel which illustrated Figure 3-41. In this case, reducing thickness of the panel can reduce the mass, but it must be sufficient for the maximum stress to be below the yield strength. Table 3-14 summarizes the design requirements for the light, strong panel.

Table 3-14: Yield-limited design requirements for the light stiff panel

Function	Panel in bending
Constraints	Panel must support bending load F without yielding
	Length L and width b specified
Objective	Minimize the mass m of the panel
Free variables	Choice of material
	Choice of panel thickness h

3.2.3.1. Background theory

The objective function is to minimize the mass of the panel.

$$m = AL\rho = bhL\rho \qquad (30)$$

Where

m = mass of the panel, kg

b = depth of the panel, m

h = thickness of the panel, m

L= length of the panel, m

ρ = density of panel, kg/m^3

The maximum stress σ_Y occurs at the surface, at the greatest distance y_m from the neutral axis due to applied moment M, but it should be smaller than yield strength of the material.

$$\sigma_Y = \frac{My_m}{I} = \frac{M}{Z_e} \qquad (31)$$

Where

σ_Y = maximum stress, MPa,

y_m = the greatest distance from the neutral axis, mm

I= second moment of area of panel, m^4

M = moment, Nm

Z_e = elastic section modulus m^3

For a rectangular section, Ze which is called the elastic section modulus is $bh^2/6$. By eliminating the free variable h the equation below can be obtained.

$$m = (6bM)^{1/2} L(\frac{\rho}{\sigma_Y^{1/2}}) \qquad (32)$$

Since the quantity M, L, b are all specified, the only free quantity that can vary is σ_Y and ρ of material. The best material for a light, strong panel is those with the largest values of $\sigma_Y^{1/2}/\rho$.

$$M = \frac{\sigma_Y^{1/2}}{\rho} \qquad (33)$$

Where

M= index

σ_Y =Yield strength, MPa,

ρ = density of panel, kg/m^3

3.2.3.2. Results and analysis

Strength is different from stiffness. This can be thought as a measure of force needed to break the springs. In brittle materials such as ceramics and glasses, breaking the materials means the solid fractures. However, in ductile materials such as polymers and metals, they hardly break and form new shape.

The procedure for yield-limited design is much as before-taking logs for equation (33) and plotting the straight lines. The higher index guarantees higher elastic limit of the materials. The cork composites have slightly lower values of M than those of GFRP, but they have similar performance functionality with some ceramics and light metals considering the density-strength relationship.

Table 3-14: Index value of cork composites and GFRP

	Density ρ (Mg/m^3)	Strength (MPa)	Index M
Cork composites	0.58-0.73	9.12-48.69	5.2-9.55
GFRP	1.36	207.95	10.6

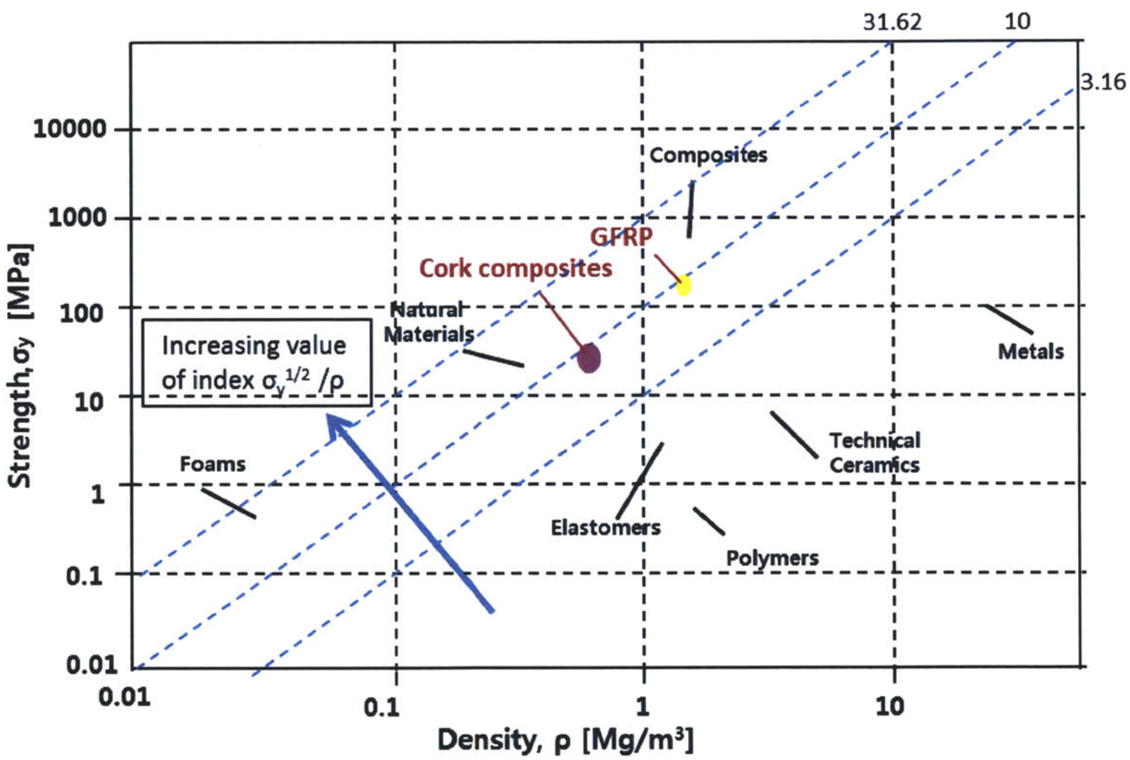


Figure 3-43: A schematic density-strength chart showing guidance for light, stiff panel

3.2.4. Fracture-limited design

It is a common rule to choose the materials that have high fracture toughness

K_{1c}. Furthermore it is known that engineering polymers have smaller values of K_{1c} [4]. Since the cork composites consist of polymer, they have inherently low fracture toughness. However, since fracture toughness is important factor to check the possibility of cork composites as a structural material, it should be compared with other materials. When fracture-limited design examined, there are several designs limited in load, energy or deflection for fracture-limited design in terms of applied load configurations. For a panel design, it should be load-limited design as shown in Figure 3-44 since the structural member of a bridge or an aircraft will fail in a brittle way if the stress exceeds fracture toughness value of material used.

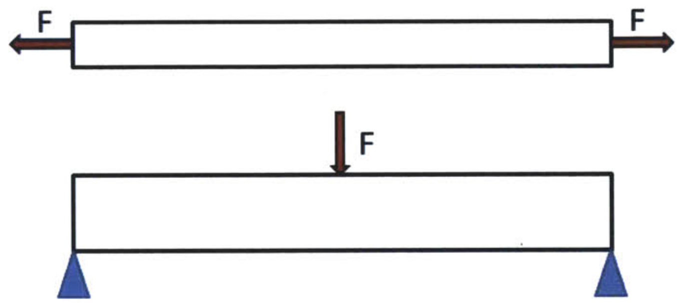


Figure 3-44: Load-limited design

To maximize the load the material has the highest value of K_{1c} is desired. Therefore, the index for fracture limited design becomes K_{1c} itself.

$$M = K_{1c} \tag{34}$$

Where

M= index

K_{1c} = Fracture toughness, $MPa.m^{1/2}$

Table 3-15: Index value of cork composites and GFRP

	Density ρ (Mg/m^3)	Fracture toughness K_{1c}, M
Cork composites	0.58-0.63	0.16-0.54

If a material easily crack or tear from the scratch, it means that material has low fracture toughness. Materials with low fracture toughness are strong until they are free from cracks, but as soon as they are damaged they break easily. Meanwhile high fracture toughness means that materials have high resistance to the propagation of a crack. They still carry loads safely when they cracked.

Gc is called toughness and this value is related to the fracture toughness K_{1c} in the following way.

$$G_c = \frac{K_{1c}^{\ 2}}{E} \tag{34}$$

Where

G_e= energy release rate

K_{1c} = Fracture toughness, MPa.m$^{1/2}$

E = Young's modulus, GPa

Figure 3-46 schematically shows the relationship between modulus and fracture toughness of materials with guidance for light, stiff panel design. Cork composites turn out to have Gc value of 1, and this is 10 times smaller than that of GFRP. This means cork composites are relatively easy to propagate of cracks. This result seems to be reasonable since the cork composite is particulate composite consists of cork granules. This makes easy segregation at boundaries of granules and intergranular cracks.

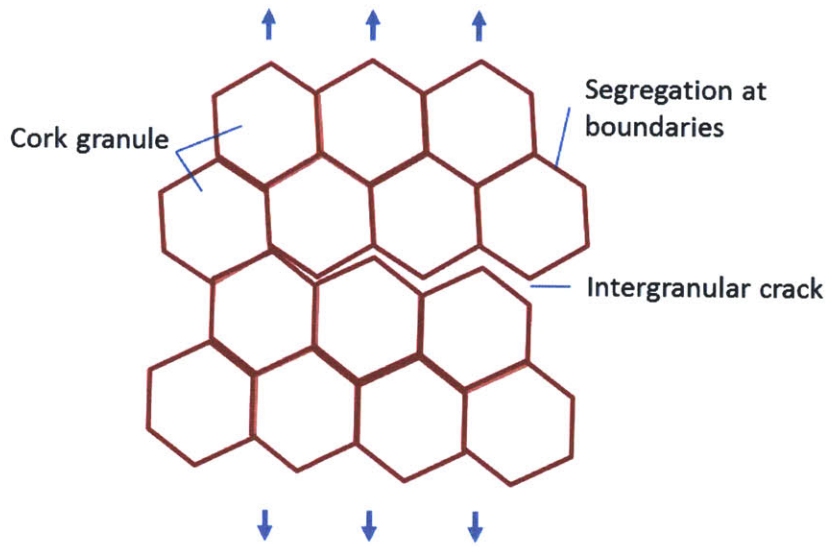


Figure 3-45: Segregation of cork granules can cause brittle intergranular cracking

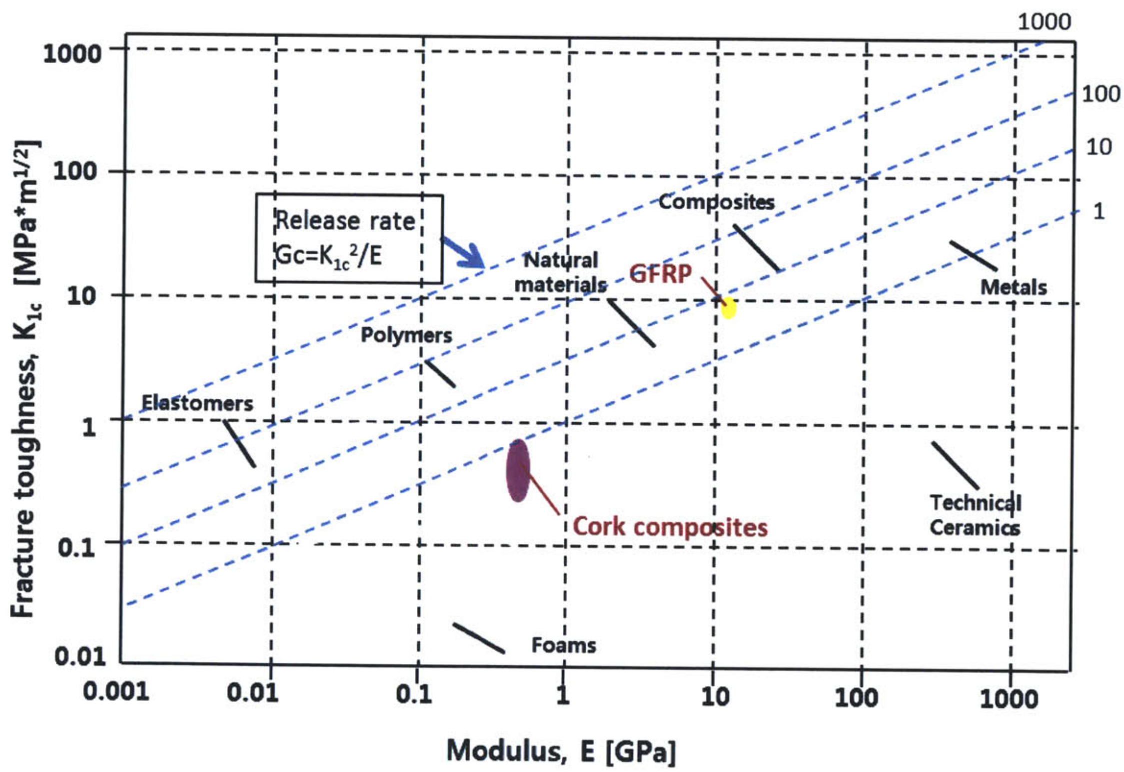


Figure 3-46: A schematic modulus- fracture toughness chart showing guidance for light, stiff panel

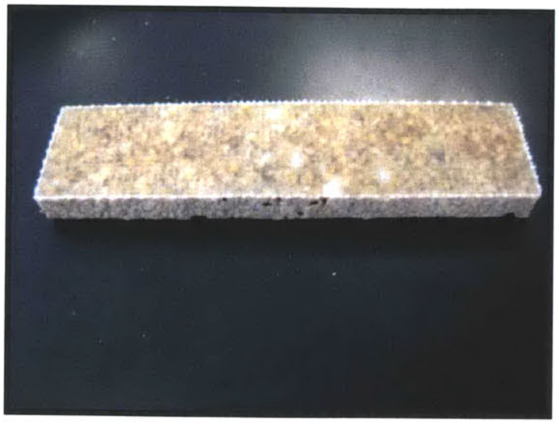
Chapter 4 Economic Analysis

4.1. Background theory

Sandwich panels are widely used in lightweight structures due to their high in-plane and flexural stiffness-to-weight ratios. This work has been exploring the use of cork-based plastic composite core material, with the goal of developing a material that is structurally competitive for typical core material applications. However, minimizing cost is a typical objective function in material design. Therefore, through this part, economic benefit of using cork composites in sandwich panels will be discussed.

4.1.1. Sample preparation

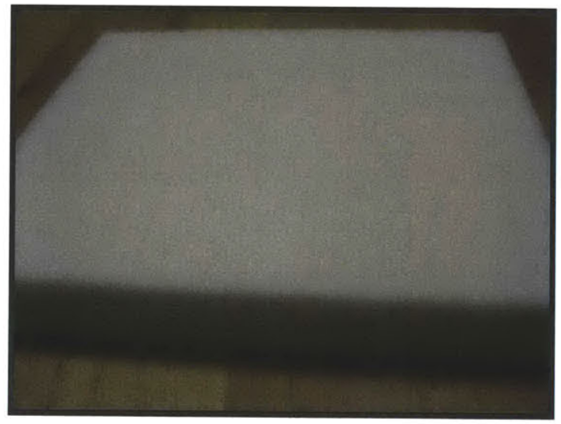
The most important mechanical property of sandwich panels is bending property since sandwich panels are designed to resist against bending force applied. In order to observe behaviors of cork composite in sandwich panels, one layer of E-glass plane woven fabric is attached as a facing material on both sides of cork composite. This facing material is also used for honeycomb core (Nomex aramid fiber honeycomb), and polyethylene terephthalate (PET) foam core. GFRP samples are also fabricated and tested as a reference specimen to compare the mechanical properties with other sandwiched panels since it is well known as a high end quality composite material. Honeycomb core and foam core are provided from the Plascore Inc. and NIDA Core Inc. respectively. The facing is added in the lab for the comparison with the cork composite with vacuum bagging setup. Thus, the values obtained from bending tests in the lab could be different from the data sheets of materials distributed in the market. In this study, it is considered to be fair to compare results with the same facing materials for all core materials since facing material also affects the behavior of sandwiched panels.



(a) Sandwiched cork composite

(b) Sandwiched honeycomb

(c) GFRP



(d) PET

Figure 4-1: Sandwiched panels for bending tests

4.1.2. Bending properties of sandwiched panels

The reason that sandwiched honeycomb has lower strength compared to its higher flexural modulus is because the area of honeycomb core attached to facing was less than other materials. Therefore, detachment of facing from the core happens at small value of load and that load was recorded as a flexural strength even though full fracture of the panel has not been happened yet. The core materials used in this study are (a) Honeycomb core, (b) Aramid fiber 1/4" (Plascore Inc.), (c) Foam-PET 1/4" (NIDA core Inc.), and (d) GFRP -

Chopped glass stranded mat and epoxy resin (West system Inc.) fabricated in the lab. Table 4-1 shows the bending properties of sandwiched composites tested.

Table 4-1: Bending properties of sandwiched panels

	Sandwiched cork composite	Sandwiched honeycomb	PET-foam	GFRP
Density (kg/m^3)	670	100	200	1,360
Flexural Modulus (GPa)	4.69	5.91	2.34	8.92
Flexural strength (MPa)	40.71	10.32	25.74	207.95

4.2. Economic analysis of sandwiched panels

4.2.1. Rigidity calculations

To do an economic analysis of cork composites in sandwiched panels, a panel like a table top is chosen as an application to compare the prices of it when it is made out of each core material. Rigidity relationship as defined in equation (35) is set up that the rigidity of the cork composite should be the same as the rigidity of other sandwiched panels to see how much cork composites is required to have similar functionality.

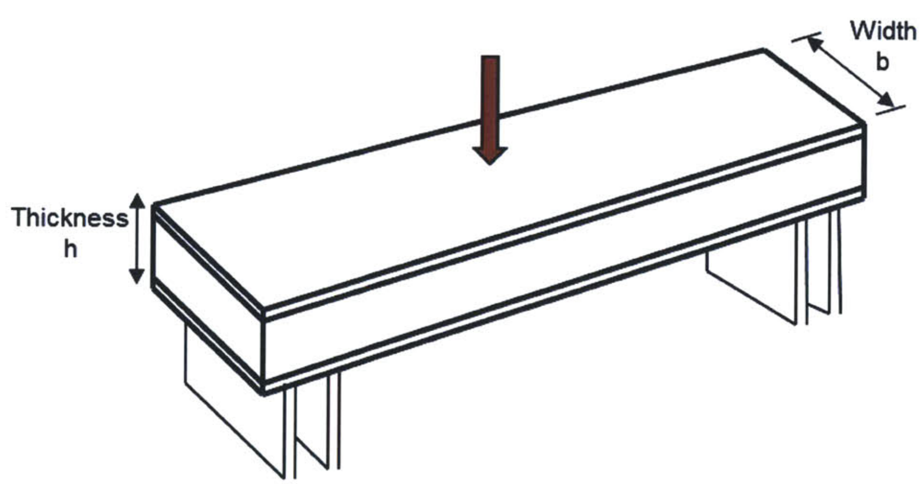


Figure 4- 2: A table top as a sandwich panel application

$$EI)_{cork} = EI)_{GFRP} = EI)_{honeycomb} = EI)_{PET} \quad (35)$$

Where

E = bending modulus of each sandwiched panel, GPa

I = the moment of inertia, m^4 ($I=bh^3/12$)

b = width of a table, m

h = thickness of a table top,m

<u>Comparison with rigidity of GFRP</u>

$$4.69*h^3_{cork\ composite}=5.91*h^3_{GFRP}$$

$$h_{cork\ composite} = 1.24*h_{GFRP}$$

This means in order for sandwiched cork composites to have similar functionality with GFRP, its thickness should be 1.24 times thicker than that of GFRP.

<u>Comparison with sandwiched honeycomb</u>

$$4.69*h^3_{cork\ composite}=5.91*h^3_{honeycomb}$$

$$h_{cork\ composite} = 1.08*h_{honeycomb}$$

<u>Comparison with sandwiched PET</u>

$$4.69*h^3_{cork\ composites}=2.34*h^3_{PET}$$

$$h_{cork\ composites} = 0.8*h_{PET}$$

Table 4-2 represents the thickness of each core material in the sandwiched panels in order for cork composite to have similar functionality in terms of rigidity.

Table 4-2: Thickness comparison for each sandwiched panel

	Cork composite	**Honeycomb**	**PET-foam**	**GFRP**
Relative thickness of core material	1	0.9	1.25	0.8

4.2.2. Price calculations for unit volume of each material

The fabrication cost of the sandwiched cork composite of unit volume is calculated. To make To make ¼" ×10"×10" of cork composites seen from Figure 4-3, 20 g of cork granules, 15 g of adhesive fibers and 180 ml of epoxy resin are needed approximately. Manufacturing cost (*i.e.* mold design, electricity, *etc.*), and the facing material are not considered.

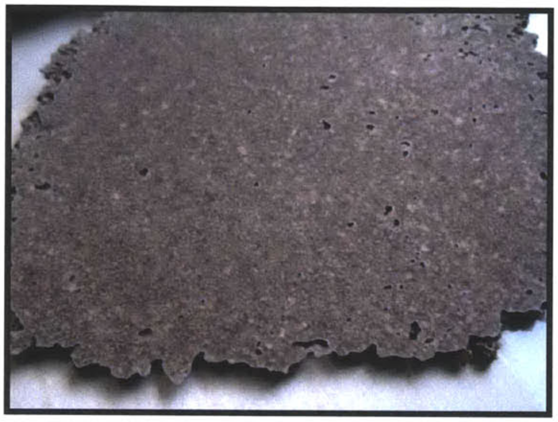



Figure 4-3: ¼" × 10" × 10" of cork composite and GFRP

- The cost of 20 g of cork granules is $ 0.1. ($ 5 per 1 kg of cork granules, Amorim company)
- The cost of 15 g of adhesive fibers is $ 0.4. ($ 20 per 20 oz of adhesive fibers, West system)
- The cost of 180 ml of epoxy is $ 4 ($ 80 per 1 gallon of epoxy resin, West system)

Therefore, the total cost for ¼" × 10" × 10" of cork composite is $ 4.5. Table 5-3 shows the prices of each composite material for unit volume 1 m^3.

Table 5- 3: Price comparison for each core composite material

	Cork composite	Honeycomb	PET-foam	GFRP
Price ($\$/m^3$)	11,250	2,487,000	7,500	16,700

4.2.3. Conclusion

Through this economic analysis study, the bending properties of each sandwiched panel are calculated to find the thickness of each panel that has equivalent rigidity. Price for each core material was also calculated using current market price. Table 4-4 represents the price of each core material for having similar functionality. Cork composite is cheaper than GFRP and honeycomb but expensive than PET-foam.

Table 4-4: Price comparison for each core composite material for equivalent rigidity

	Cork composite	**Honeycomb**	**PET-foam**	**GFRP**
Relative thickness of core material	1	0.9	1.25	0.8
Price ($\$/m^3$)	11,250	2,487,000	7,500	16,700
Price for similar functionality	**11,250**	**2,238,300**	**9,375**	**13,360**

For ease of price calculation, the rectangular shape of application was adopted in this study. Thus, the manufacturing cost was not considered. However, due to difficulty for foam and honeycomb to fill and shape of curved structures that have varying thickness, their manufacturing cost could demand long time and lots of man power. For cork composite once you have designed mold, then complicated structure can be obtained with compression molding or Resin Transfer Molding process. It could be conclude that that cork composite material is competitive in terms of mechanical properties, ease of fabrication and the material and fabrication cost. This result is represented in Figure 4-4

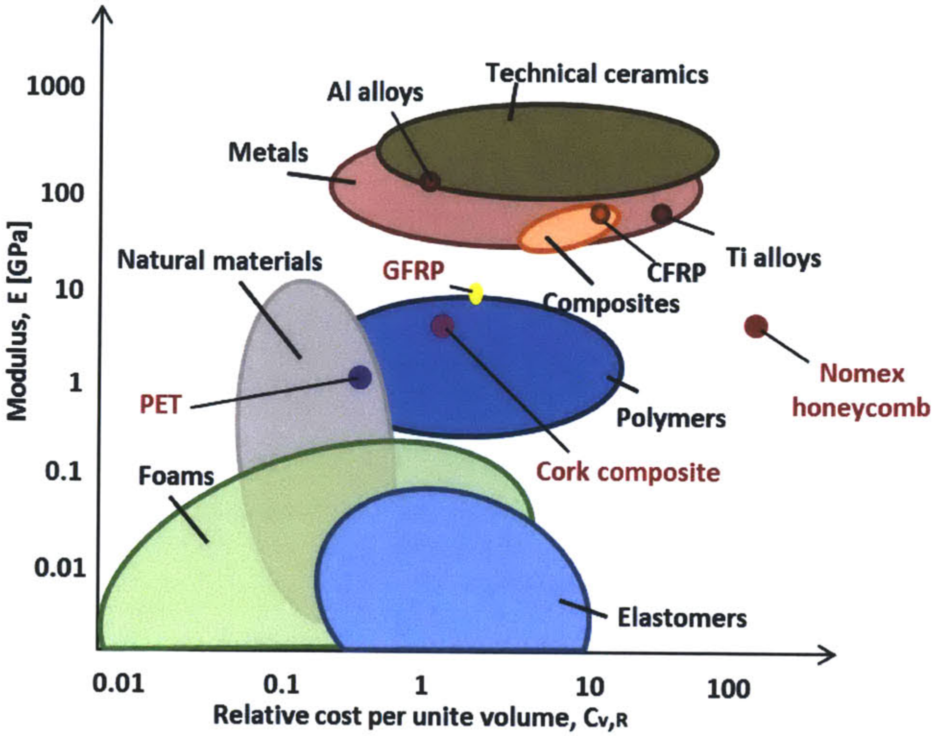


Figure 4-4: A schematic relative cost per unit volume-modulus showing economic analysis result for a top table application

Chapter 5 Environmental Impact Analysis

5.1. Background

From the designer's point of view, it could be an ideal situation that gaining all information clearly indicates all significant factors of a multicriteria decision problem. Environmental information about materials is necessary if we are to finish material design. [20]. It is considered that there is an important relationship between material-design and eco-design, in the sense that eco-design tries to incorporate more eco-friendly materials in order to decrease environmental burdens. Life cycle assessment (LCA) is a methodological tool used to analyze the life cycle of products/activities quantitatively. It was initially generated to compare clearly defined end product alternatives, but later on it is rapidly incorporated into higher strategic levels. It is known that there is no single standard method that is applicable in all situations, thus at international level, an ISO-standard (the 14040-series) was established. However, due to autonomously developments in LCA, discrepancies between assessment methods have been arisen. [21]

5.1.1. Life Cycle Assessment (LCA)

According to ISO 14040, LCA consists of 'goal and scope definition', 'life cycle inventory', and 'life cycle impact assessment' and 'interpretation'. In LCA, every step is meaningful, but it is considered to be an LCA when they are mutually connected as seen in Figure 5-1. 'Life cycle improvement assessment' is not the part of LCA in ISO 14040 since it cannot be quantified and standardized.

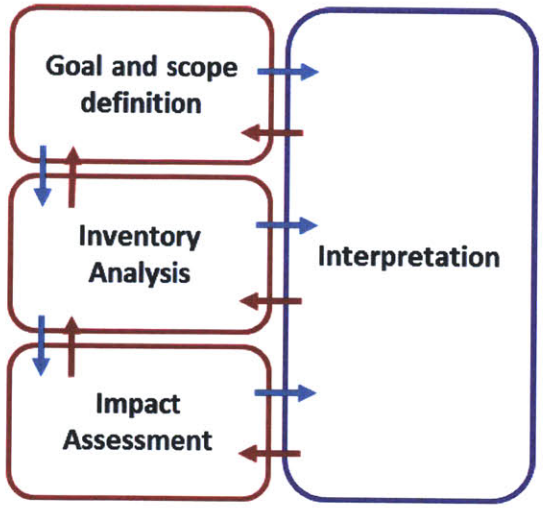


Figure 5-1: LCA performance stages, ISO 14040[22]

5.1.2. LCA methodologies

There are two main approaches to conduct LCA: process analysis and input-output analysis.

5.1.2.1. Process analysis

Most currently used LCA methodology is process analysis. It involves the detail investigations on how a material or system is manufactured and disposed regarding used materials and manufacturing processes. This approach is mainly developed by the Society for Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental protection Agency (USEPA). [23] Defining the boundary of a system is a significant issue for this approach.

Each stage consists of 'assessment', 'analysis' and' improvement'. In 'assessment' stage, the goal is to quantify the environmental effect of each stage of LCA. It is pursued to apprehend all materials input and environmental output of each stage since all inputs and outputs are separated in the form of independent process models. However, it is so time consuming and uneconomical to quantify every single process that constitutes one system or process for this approach. Therefore, this approach is conducted on several processes and materials considered to be most important in analysis. In "analysis" stage, the level and aspect of previously assessed environmental effects of a material or a system is investigated. Lastly in improvement stage, the examination and comparison with a system or process that has similar boundary conditions are conducted in order to induce the improvement for reducing the environmental effects.

The merit of the process analysis is that the substance and cause of environmental loads of a system or a process are clear, thus the quantitative assessment and analysis can be made. However, there are also few disadvantages of the process analysis.

- ✓ There is a limit on the process that can be processed and processing all sub-processes is impossible.
- ✓ The comprehensive data is short.
- ✓ The reliability of the data raises questions.
- ✓ There is no commonly acceptable and agreeable LCA in this approach.
- ✓ It is unclear that how broad the boundary should be to get reliable data.

5.1.2.2. Input-output analysis

This approach is based on model of industrial activity and pollution discharge data. It considers all fractions of the total environmental discharges associated with the product or process. [22]. The estimation covers all environmental burdens, so overall comprehend is possible and the results of estimation are considered to be objective. The merit of this approach is described as follows.

- ✓ Analysis range is expandable.
- ✓ Reproducibility is high.
- ✓ The result is objective.

However, the data contains insufficient information for a system or a process since the values are simply averaged.

5.1.3. Stages of LCA

1. Goal and scope definition

The purpose and basic requirements of study are defined.

2. Inventory Analysis

Technical data gathering for evaluations on energy, raw material requirements, emissions, wastes for processes, materials are in this stage. Assumption used, the boundary, the basis for comparative claims are included.

3. Impact Analysis

The effects of impacts on environmental issues are determined by evaluating the technical, quantitative, and qualitative efforts.

4. Improvement analysis

This step aims to evaluate the opportunities to reduce environmental impacts and issues found in steps 1and 2.

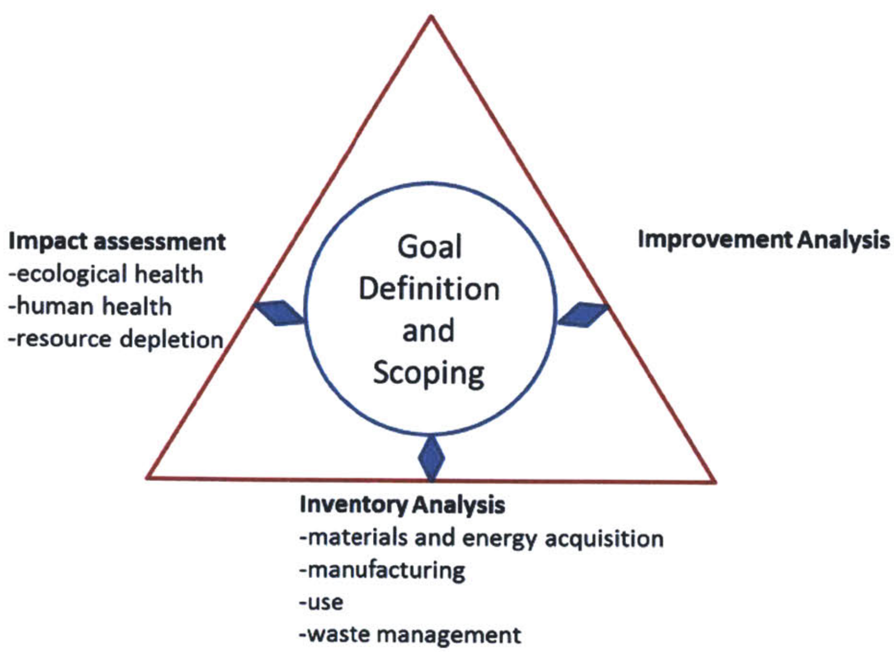


Figure 5-2: Mutual relationship of LCA performance stages [22]

5.1.3.1. Goal and scope definition

The product or service to be assessed is defined and functional unit for comparison is selected. The goal definition of performing LCA is to simply answer questions such as "Where the results can be applied to", "What is the reason to perform LCA", and "Who are you proposing the results to". However, the scope definition is not that simple due to lots of complicated basic parts that should be assessed. Function and functional unit, system boundary, and requirements for data quality are the parts of scope definition. The range and the depth of performing LCA should be set up encompassing all aspects specified in goal definition and assumption should be clear to guarantee transparency of the performed LCA.

Function, functional unit and reference flow

To define the function of a system is to define what the system is used for. The use of the system should be prescribed from user point of view. The functional unit is a criterion that enables the system to be assessed their performance. Therefore, the functional unit should be measurable and converted into weight-scale. The functional unit is the control point where the input and output are connected.

System boundary

All processes related to the system should be inside the system boundary in principle. The system consists of main process that manufactures the system itself, and upstream /downstream processes. If product doesn't exist, the upstream/downstream processes would not exist either. Therefore, the product is responsible for all induced environmental loads. This is why the system boundary definition should be understood carefully. Determining the boundary of LCA is critical. If it is too narrow, many important issues will be omitted from the assessment, meanwhile if the boundary is too broad, data mining is will be expensive and time consuming.

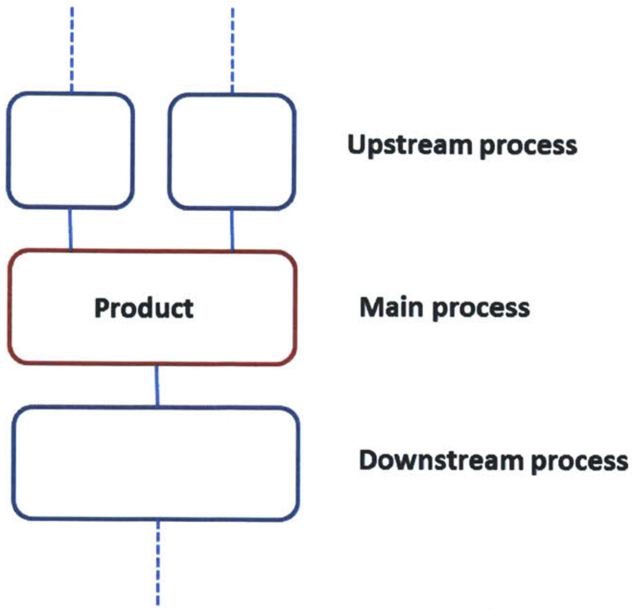


Figure 5-3: Product and processes

However, it is hard to keep all processes inside the system boundary due to time, cost, short of data, and limit of main usage. The important thing is that rational and transparent reasons for cut off criteria should be notified. In general, the subjects that should be in the system boundary are raw materials; energy input; transportation; electricity; heat; subsidiary materials production; and waste from processes. It is important to set up the interrelation between processes and this can be conducted as drawing process trees.

<u>Input/output</u>

Inputs are main raw materials, subsidiary materials and energy. Outputs are the product and emission to air, water and land.

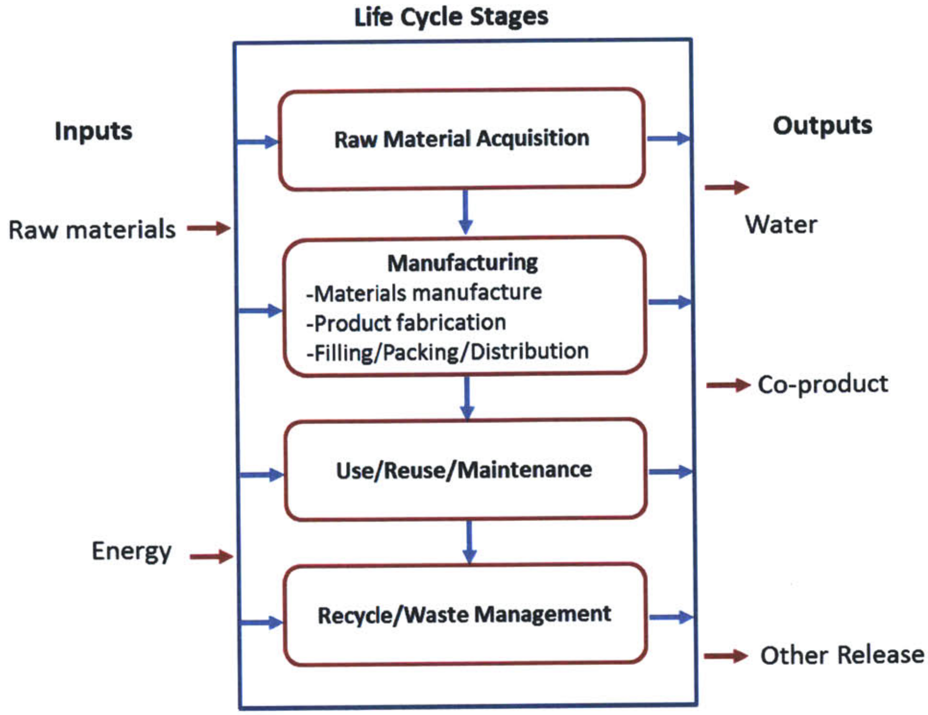


Figure 5-4: A diagram presenting system boundary and input/output

Allocation

If the waste from the system is used as a raw material of other systems, the loop recycling is open and allocation becomes significant issue.

Abridgement of level of process or data request

The transportation and internal transportation can be omitted.

Data category and quality requirement

Data for LCA is collected in order to quantify the inputs and outputs for all unit processes. Data is broadly classified into resources, energy, water, air and the environmental loads for generating electricity. Based on ISO 14041, accumulated weight, energy and relationship to environments decides the initial inclusion level. The quality of the collected data affects the results of LCA. Therefore, time, geographical and technical coverage should be carefully considered. Even after collecting vast data, data retouching is normally followed for LCIA, but time for data collecting and retouching can be reduced by setting up valid assumptions.

5.1.3.2. Life Cycle Inventory Analysis (LCI)

LCI is the process that quantifies the inputs and outputs of systems. It consists of upstream/downstream processes, and the process for the system focused to be analyzed. Process tree refers to the process flow diagram that represents mutual relationship between every unit process existing inside the system. There are main process tree and sub process trees. The main goal of LCI stage is to collect input/output data of the processes that appeared in the process trees. Every process includes tremendous information, thus data collecting is so time and money consuming work. It also happens that data collecting is impossible for some processes. Then, the system boundary and data quality requirements could be revised and this is one of characters of performing LCI which is called iterativeness. This is graphically described in Figure 5-5. The methodology used for this inventory should be consistent with the methodology for Life Cycle Inventory (LCI) in the ISO 14040 standard documents, specifically 14040, 14041, and 14043. However, diverse environmental profile database for materials has been accumulated and compiled in different commercial LCI databases.

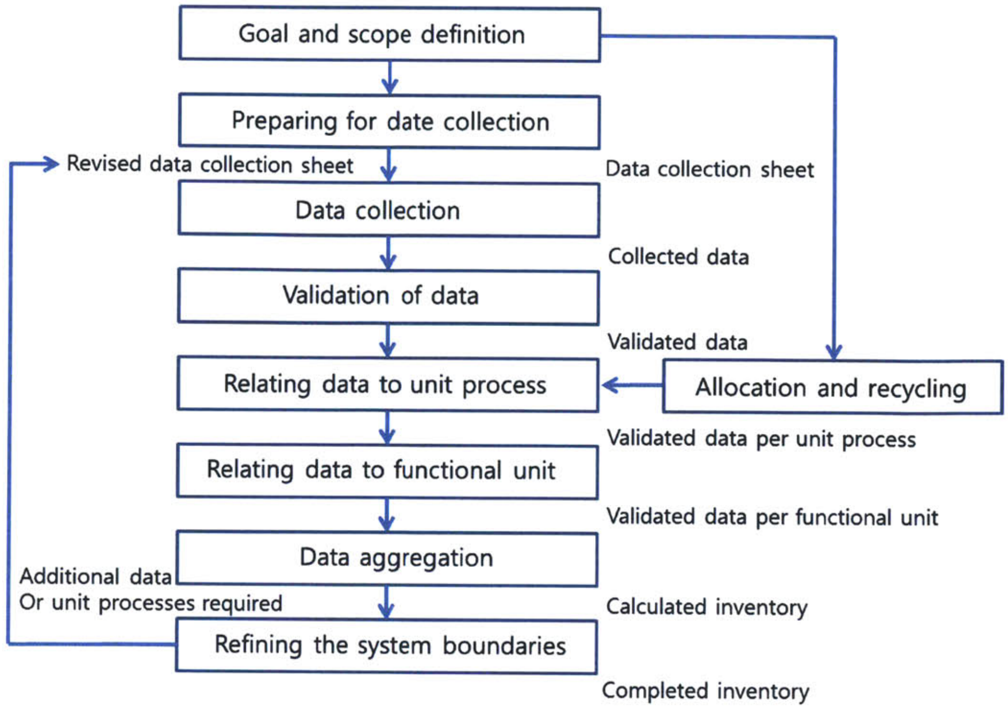


Figure 5-5: Iterative character of conducting LCI, ISO 14041

5.1.3.3. Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment (LCIA) is a process in LCA that environmental loadings identified in inventory analysis stage are quantitatively and qualitatively investigated in terms of attribution to environmental and human health effects. LCIA aims at understanding and evaluating the magnitude and the significance of the potential environmental impacts of a product system.

Indicators in LCIA refer to categories such as Greenhouse effect, Ozone depletion, Acidification, Eutrophication and Natural resource depletion. Indicators do not deal with quantitative inventory data that measure mass of materials or joules of energy, but convert these. They also can be called as impact categories. Proper interpretation of the indicators and drawing sound conclusions should be emphasized in understanding of LCIA. Most indicators are "directional" to a greater or lesser degree. [24] It should be kept in mind that the values from indicators may wrongly induce the results seems to be absolute and meaningful. Indicators differ widely in how they relate to the environment and the assumptions used to derive them. [24] LCIA does not pursue to determine actual impacts, but rather to connect the data collected from the inventory to impact categories and quantify the relative magnitude of contribution to the impact categories [23]

LCIA methods

In LCIA, two methods are followed: problem-oriented methods (mid points) and damage-oriented methods (end points). [2]

Midpoint method

In the midpoint method (problem-oriented approaches) flows are classified into environmental themes to which they contribute. The theme covers: greenhouse effect (or climate change), natural resource depletion, stratospheric ozone depletion, acidification, photochemical ozone creation, eutrophication, human toxicity and aquatic toxicity. Simplifying all complicated flows into a few environmental areas of interest is the purpose of this method. An important issue with problem-oriented methodologies is the communication aspect of the results since it is hard to connect cause and result directly.

Endpoints method

The endpoint method (damage-oriented method) tries to create the correlation between environmental theme's damage listed above and human health, ecosystem health or damage to resources. Figure 5.6 shows a simplified representation of the midpoint and end point approach to climate change.

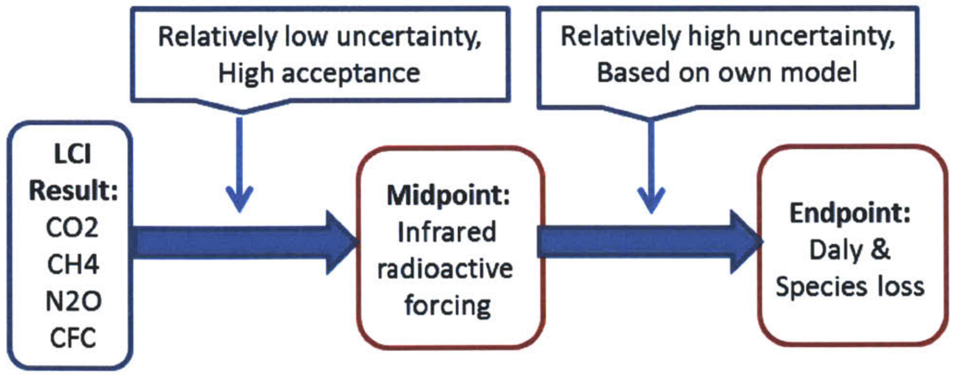


Figure 5-6: Midpoint and Endpoint approach for climate change [21]

Key Steps of LCIA

The following steps comprise a life cycle impact assessment.

1. Selection and Definition of Impact Categories

- Identifying relevant environmental impact categories (e.g., global warming, acidification, terrestrial toxicity).

2. Classification

- Assigning LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming).

3. Characterization

- Modeling LCI impacts within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).

4. Normalization

- Expressing potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options).

5. Grouping

- Sorting or ranking the indicators (e.g. sorting the indicators by location: local, regional, and global).

6. Weighting

– Emphasizing the most important potential impacts.

7. Evaluating and Reporting LCIA Results

- Gaining a better understanding of the reliability of the LCIA results.

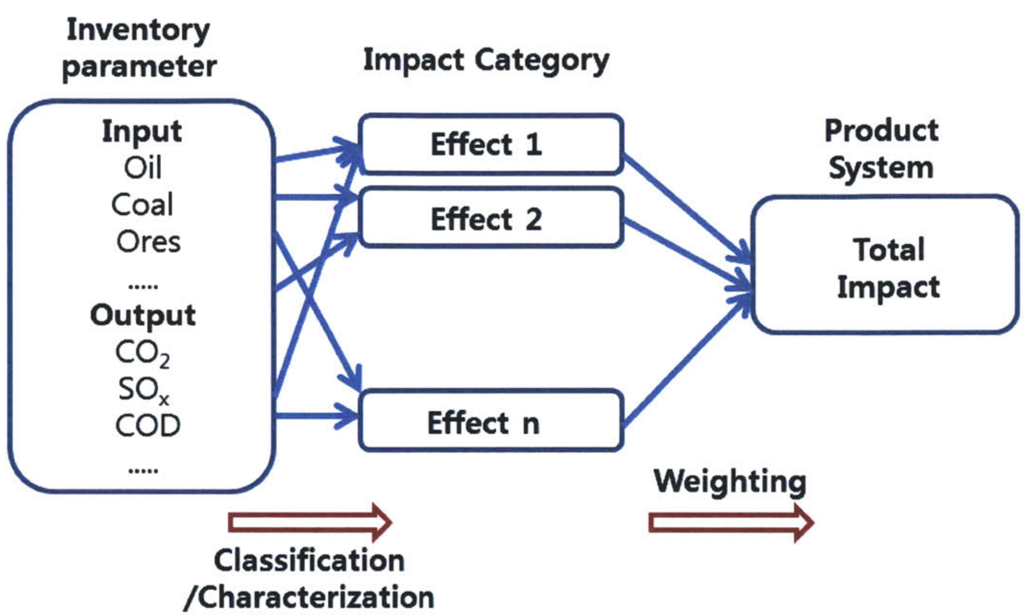


Figure 5-7: Approach to LCIA from LCI results [25]

Classification

Inventory parameters from LCI should be assigned into the impact category groups. Classification mainly consists of two steps: linking and grouping. Linking is the operation that qualitatively links inventory parameters to the effects which they can possibly affect based on scientific facts. Grouping is to pull all inventory parameters together into the specified effects. By doing classification, the type of effects that inventory parameters affect could be figured out. Table 5-1 shows frequently used impact categories for classification of eco-indicator 99.

Table 5-1 Impact and Damage category of eco-indicator 99

Impact category	**Unit**	**Damage category**
Carcinogen	DALY	Human health
Resp. organics	DALY	
Resp. inorganics	DALY	
Climate change	DALY	
Radiation	DALY	
Ozone layer	DALY	
Ecotoxicity	PAF*m2yr	Ecosystem quality
Acidification/Eutrophication	PDF*m2yr	
Land use	PDF*m2yr	
Minerals	MJ/plus	Resources

Characterization

Impact parameters assigned into the impact category are needed to be quantified in order to apprehend their effects. Equation (36) descripts the procedure of characterization theoretically.

$$C_{i,j} = Load_J * eqv_{i,j} \qquad (36)$$

Where

$C_{i,j}$= impact of jth inventory parameter on ith impact category

Load j= environmental load of jth inventory parameter, g/f.u.

f.u.= functional unit

$eqv_{i,j}$= Equivalency factor of jth inventory parameter in ith impact category

$$CI_i = \sum_j C_{i,j} = \sum_j (Load_J * eqv_{i,j}) \qquad (37)$$

Where

CI_i= Summation of potential impacts of inventory parameters on ith impact category

Normalization

Normalization is needed in order to identify the unit of each impact category and clarify the relative importance within a certain period of time and certain area. This is to obtain normalized impact NI_i and can be conducted by dividing the result from characterized impact CI_i with normalization reference N_i.

$$NI_i = \frac{CI_i}{N_i} \quad (38)$$

Where,

NI_i= normalized ith impact

CI_i=characterized ith impact

N_i.= ith normalization reference

Weighting

Considering the overall effects of all impact categories on overall environments, the relative importance is decided and interpreted with social, moral, and scientific point of view. There are two ways to weight: quantitative approach and qualitative approach. Quantitative approach allows us to judge the environmental preference in the form of better, worse, or equal while qualitative approach provides narrower measure to deduct the numerical value. Decision methods for weighting factor of LCA [25]

$$WI_i = W_i * CI_i \quad (39)$$

Where

WI_i= weighted impact of ith impact category

W_i= ith weighting factor

CI_i= characterized i_{th} impact

Table 5-2: Descriptions of qualitative approaches of LCIA weighting [25]

Qualitative approaches	Description
Expert panels	✓ Method; questionnaires, interview or group discussion ✓ Group of panelist; experts, stakeholders or lay-people ✓ Procedure; one-round or multi-rounds procedure
Monetization	✓ Similar to the panel method ✓ Similarity; people are asked to distribute points on the different impact categories ✓ Difference; people are asked to put monetary value on the impact category
Distance to target	✓ Relating the weighting factor(w_i) to some sort of target ✓ Target; standards, environmentally quality, political reduction targets

5.2. Environmental impact of cork composite and GFRP

5.2.1. Goal and scope definition of cork composite and GFRP

Products/ processes to be assessed through this study are cork composites and GFRP fabricated in the lab. The purpose of this study is to quantify the environmental loads and establish the environmental issues of the cork composites by LCA. Furthermore, it is expected to offer a comparison with GFRP through this study.

5.2.1.1. Function, functional unit and reference flow

As an exterior material, the function is defined as to resist against the shear, compressive, and bending force as a core material. The functional unit can be defined as a volume that the cork composites can stand a certain amount of external load as a core material inside sandwich structures. The reference flow in this study is set up to be the mass of cork composites volume specified in order to function. Turn table is the possible application and the dimension of the turn table in this study is assumed to be 0.025 m x 1m x 1m. The mass of tables made of the cork composites and GFRP are calculated as the reference flow.

5.2.1.2. System boundary

The boundary of the system is defined as cradle to gate referring to from row material data acquisition to before utilizing the product and all general processes in between are investigated.

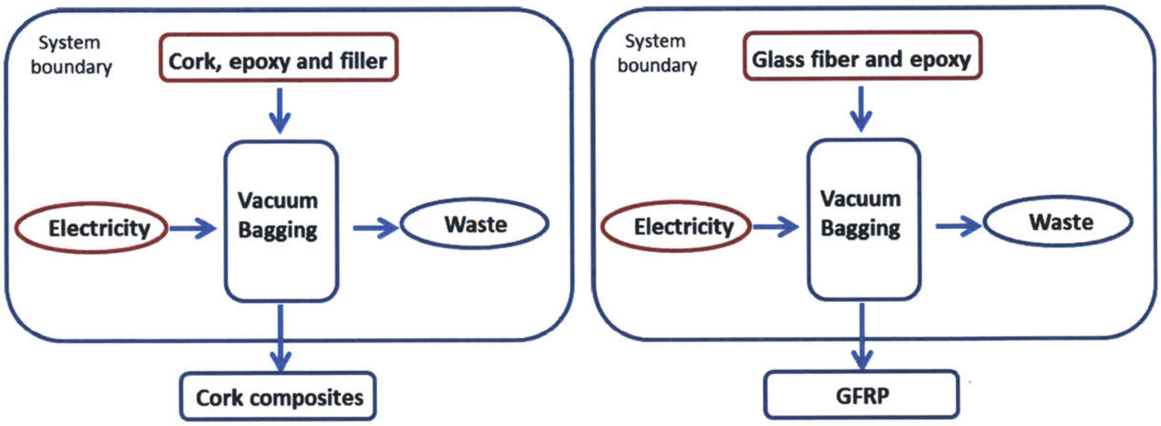


Figure 5-8: System boundary of the cork composite and GFRP

Input/output

The main raw materials are cork and epoxy and subsidiary materials are additional filler to the cork composites to fortify its material properties. The main raw materials of GFRP are glass fiber and epoxy and no filler used. The only energy used for fabrication both is electricity.

Allocation

There is only one process that needs electricity: vacuum bagging for 7 hours for curing steps. Therefore, the electricity consumed is electricity amount that compressor requires to run 70 psi.

Data quality

For time coverage requirements, it is targeted to get most recent data. The geographical coverage of the main/subsidiary material is mainly local product region.

However, cork used for this study is from Portugal. Under the consumption that cork can be cultivated in US area, the effect of transportation is omitted. The technological coverage targets the manufacturing processes for fabrication of the cork composites. The dashed box of Figure 5-9 indicates the boundaries of LCI analysis for this study. For this cradle-to-gate LCI of the cork composites and GFRP, LCI database including U.S. Life Cycle Database is used.

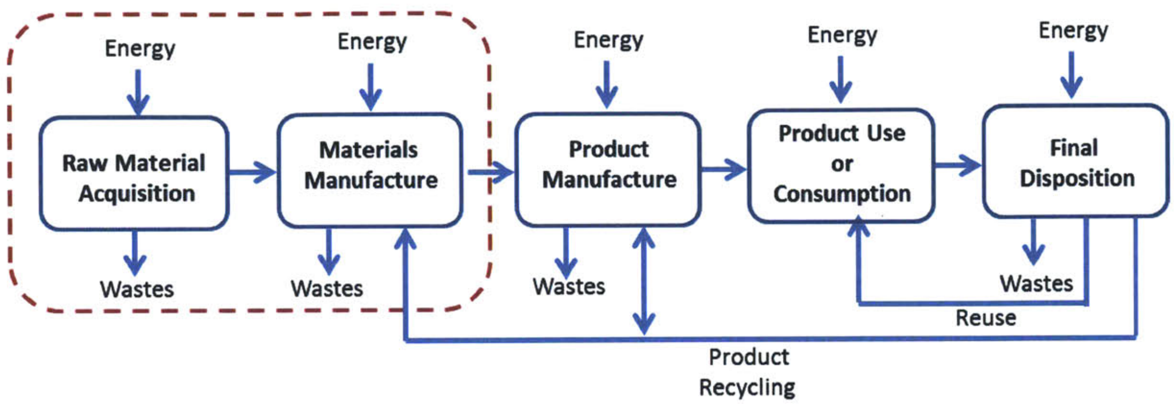


Figure 5-9: General materials flow for "cradle-to-grave" analysis of a product system

Fabrication data

All materials that constitute the cork composites and GFRP during fabrication are listed on Table 5-3, 5-4 respectively and they contain the weight and percentage mass.

The power consumption during the fabrication is calculated based on the power specification of the compressor used. The compressor named D55168 from DeWALT company is used and it has 1.6 HP (1194 watts) specification and it should run 7 hours for the composites to be cured. This value can be converted into 8,355 watts for unit process.

Table 5-3: Cumulative mass of constituents of the cork composite

Material	Weight(g)	Mass (%)	Cumulative mass (%)
Cork	320	3.53	3.53
Filler	240	2.65	6.18
Epoxy resin	8,500	93.82	100
Total	9,060	100	100

Table 5-4: Cumulative mass of constituents of GFRP

Material	Weight(g)	Mass (%)	Cumulative mass (%)
Fiber glass	75,000	58.7	58.7
Epoxy resin	52,750	41.3	100
Total	127,750	100	100

Figure 5-10: The compressor D55168 from DeWALT company

5.2.2. Life Cycle Inventory Analysis (LCI) of cork composite and GFRP

Major inputs and outputs of the cork composites and GFRP are listed in Table 5-5, 5-6 after drawing LCI result. For some intermediate chemicals and all raw materials, the energy and environmental data presented are developed using the best and relatively current data available from National Renewable Energy Laboratory. Since the system boundary of this study is set to be cradle to gate, environmental burdens associated with end-of life anagement is not included in this study. Therefore, transportation of raw materials and use of product by consumer is not included either.

The methodology used in this study is consistent with the life cycle inventory methodology described in the ISO 14040 standards

✓ ISO 14040 Environmental Management-Life Cycle Assessment-Principles and Framework Reference No. ISO 14040: 1997(E)

✓ ISO 14041 Environmental Management-Life Cycle Assessment-Goal and Scope Definition and Inventory Analysis. Reference No. 14041: 1998(E)

Table 5-5: Life cycle inventory of cork composite

Major inputs and outputs					
Name	Value	Unit	Direction	Category	Media
Water	8.92E+02	kg	INPUT	Resource	Soil
Sodium chloride (NaCl)	6.37E+00	kg	INPUT	Resource	Soil
Crude oil	5.06E+00	kg	INPUT	Resource	Soil
Air	4.30E+00	kg	INPUT	Resource	Air
Natural gas	3.42E+00	kg	INPUT	Resource	Soil
Lignite	1.54E+00	kg	INPUT	Resource	Soil
Coal	1.36E+00	kg	INPUT	Resource	Soil
Natural Aggregate	1.25E+00	kg	INPUT	Resource	Soil
Waste water	1.02E+02	kg	OUTPUT	Waste	Technosphere
Industrial wastes	8.61E+00	kg	OUTPUT	Waste	Technosphere
Carbon dioxide (CO2)	2.08E+01	kg	OUTPUT	Emission	Air
Vapor	2.55E+00	kg	OUTPUT	Emission	Air
Nitrogen oxides(NOX)	8.25E-02	kg	OUTPUT	Emission	Air
Iron(Fe)	4.41E-02	kg	OUTPUT	Emission	Air
Sulfur dioxide(SO2)	4.01E-02	kg	OUTPUT	Emission	Air
Methane(CH4)	2.60E-02	kg	OUTPUT	Emission	Air
Chloride(Cl-)	6.11E-02	kg	OUTPUT	Emission	Water

Table 5-6: Life cycle inventory of GFRP

Major inputs and outputs					
Name	Value	Unit	Direction	Category	Media
Water	6.31E+03	kg	INPUT	Resource	Soil
Cullet	4.31E+01	kg	INPUT	Resource	Soil
Sodium chloride(Nacl)	3.97E+01	kg	INPUT	Resource	Soil
Crude oil	3.16E+01	kg	INPUT	Resource	Soil
Air	2.68E+01	kg	INPUT	Resource	Air
Sand (SiO2)	1.81E+01	kg	INPUT	Resource	Soil
Lignite	9.57E+00	kg	INPUT	Resource	Soil
Coal	8.48E+00	kg	INPUT	Resource	Soil
Waste water	6.80E+02	kg	OUTPUT	Waste	Technosphere
Carbon dioxide (CO2)	1.42E+02	kg	OUTPUT	Emission	Air
Air	2.59E+01	kg	OUTPUT	Emission	Air
Vapor	1.70E+01	kg	OUTPUT	Emission	Air
Industrial wastes	9.89E+00	kg	OUTPUT	Waste	Technosphere
Exhaust	5.14E-01	kg	OUTPUT	Emission	Air
Nitrogen oxides(NOX)	3.81E-01	kg	OUTPUT	Emission	Air
Chloride(Cl-)	6.80E+02	kg	OUTPUT	Emission	Air

5.2.3. Life Cycle Impact Analysis (LCIA) of cork composite and GFRP

In order to evaluate overall cork composite performance, environmental impact analysis should be investigated as a requirement for material design. Therefore, LCIA of the cork composites is necessary in order to approve that the cork composites guarantees the environmental benefits of using it over other core materials including GFRP.

According to the ISO 14044 Annex B the importance of contributions can be classified in terms of percentage. The percentage is calculated using equation (40)

$$Contribution(\%) = \frac{\sum C_{i,j}/N_i \times W_i}{\sum_k \sum_i \frac{C_{i,k}}{N_i} \times W_i} \times 100 \tag{40}$$

The ranking criteria are:

A: Contribution > 50%: most important significant influence;

B: 25% < Contribution < 50%: very important, relevant influence;

C: 10% < Contribution < 25%: fairly important, some influence;

D: 2.5% < Contribution < 10%: little important, minor influence;

E: Contribution < 2.5 %: not important, negligible influence.

Table 5-7: Factors for normalization and weighting

Impact category	N_i	W_i
Carcinogen	2.149E2	400
Resp. organics	2.149E2	
Resp. inorganics	2.149E2	
Climate change	2.149E2	
Radiation	2.149E2	
Ozone layer	2.149E2	
Ecotoxicity	1.784E-4	200
Acidification/Eutrophication	1.784E-4	
Land use	1.784E-4	
Minerals	2.878E-3	200

Most significant influence category of both cork composites and GFRP turned out to be different. For cork composites, minerals has the highest influence while ecotoxicity has the most significance influence for GFRP.

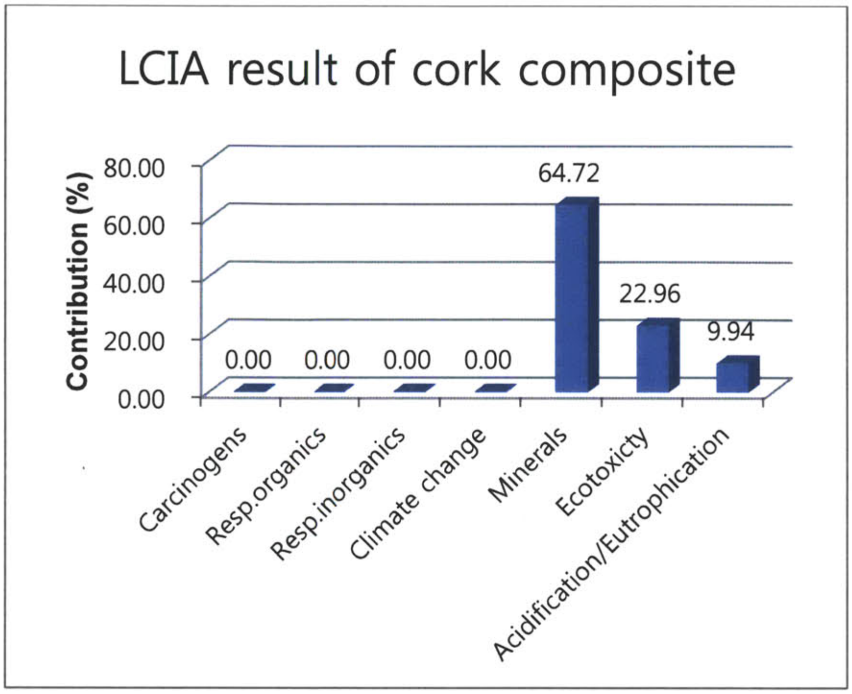


Figure 5-11: LCIA result of cork composite

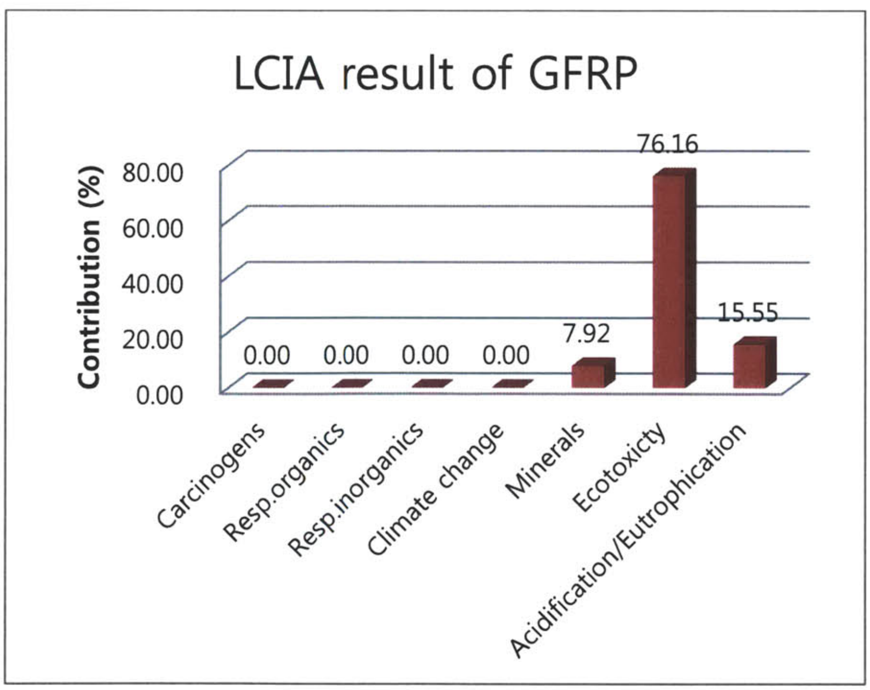


Figure 5-12: LCIA result of GFRP

Table 5-8: Key inventory parameters with impact category in cork composite

Impact Category(IC)	Material	CI	Ni	NI	WI	Total WI_i	Contribution among ICi	Contribution in total
Carcinogens	Cadmium (Cd)	4.17 E-09	2.15 E+02	1.94 E-11	1.67 E-06	3.27 E-06	51.1%	0.00%
	Cadmium, ion	1.51 E-09	2.15 E+02	7.02 E-12	6.04 E-07		18%	
	Arsenic (As)	1.23 E-09	2.15 E+02	5.72 E-12	4.92 E-07		15%	
Resp. organics	Isoprene	1.29 E-08	2.15 E+02	6.00 E-11	5.16 E-06	2.45 E-05	21%	0.00%
	NMVOC	2.55 E-08	2.15 E+02	1.19 E-10	1.02 E-05		42%	
	Propene (C3H6)	1.02 E-08	2.15 E+02	4.74 E-11	4.08 E-06		17%	
Resp. inorganics	Sulfur dioxide (SO2)	1.90 E-06	2.15 E+02	8.84 E-09	7.60 E-04	1.03 E-03	73%	0.00%
	Sulfur oxides (SOx)	5.13 E-07	2.15 E+02	2.39 E-09	2.05 E-04		20%	
	Nitrogen oxides (NOx)	1.06 E-07	2.15 E+02	4.93 E-10	4.24 E-05		4%	
Climate change	Carbon dioxide (CO_2)	4.18 E-06	2.15 E+02	1.94 E-08	1.67 E-03	2.00 E-03	84%	0.00%
	Carbon dioxide, fossil (CO_2)	6.90 E-07	2.15 E+02	3.21 E-09	2.76 E-04		14%	
	Methane (CH4)	1.16 E-07	2.15 E+02	5.40 E-10	4.64 E-05		2%	
Minerals	Nickel, (Ni)	3.31 E-01	2.88 E-03	1.15 E+02	6.62 E+01	9.78 E+01	68%	64.72%
	Copper, (Cu)	1.13 E-01	2.88 E-03	3.92 E+01	2.26 E+01		23%	
	Zinc (Zn)	1.63 E-02	2.88 E-03	5.66 E+00	3.26 E+00		3%	
Eco-toxicity	Zinc (Zn)	8.33 E-02	1.78 E-04	4.68 E+02	1.67 E+01	3.55 E+01	47%	22.96%
	Nickel (Ni)	5.55 E-02	1.78 E-04	3.12 E+02	1.11 E+01		31%	
	Chromium (Cr)	1.87 E-02	1.78E -04	1.05 E+02	3.74E +00		11%	
Acidification/ Eutrophication	Sulfur dioxide (SO2)	5.08 E-02	1.78 E-04	2.85 E+02	1.02 E+01	1.36 E+01	75%	9.94%
	Sulfur oxides (SOx)	1.37 E-02	1.78 E-04	7.70 E+01	2.74 E+00		20%	
	Ammonia (NH3)	3.67 E-03	1.78 E-04	2.06E +01	7.34 E-01		5%	
Land use	N/A	N/A	1.78 E-04	X	X	X	X	X
Radiation	N/A	N/A	2.15 E+02	X	X	X	X	X
Ozone layer	N/A	N/A	2.15 E+02	X	X	X	X	X

Table 5-9: Key inventory parameters with impact category in GFRP

Impact Category(IC)	Material	CI	Ni	NI	WI	Total WI_i	Contribution among ICi	Contribution in total
Carcinogens	Cadmium (Cd)	2.44 E-08	2.15 E+02	1.13 E-10	9.75 E-06	1.34 E-05	72.5%	0.00%
	Arsenic (As)	7.08 E-09	2.15 E+02	3.29 E-11	3.88 E-07		21.1%	
	Nickel (Ni)	9.70 E-10	2.15 E+02	4.51 E-12	2.83 E-06		2.9%	
Resp. organics	NMVOC	1.92 E-07	2.15 E+02	8.92 E-10	7.67 E-05	1.18 E-04	65%	0.00%
	Hydrocarbon	7.20 E-08	2.15 E+02	3.35 E-10	2.88 E-05		24.4%	
	Propene (C3H6)	1.60 E-08	2.15 E+02	7.46 E-11	6.42 E-06		5.4%	
Resp. inorganics	Sulfur dioxide (SO2)	1.14 E-05	2.15 E+02	5.31 E-08	4.57 E-03	6.90 E-03	66.2%	0.00%
	Sulfur oxides (SOx)	4.90 E-06	2.15 E+02	2.28 E-08	1.96 E-03		28.4%	
	Nitrogen oxides (NOx)	7.98 E-07	2.15 E+02	3.71 E-09	3.19 E-04		4.6%	
Climate change	Carbon dioxide (CO_2)	2.36 E-06	2.15 E+02	1.10 E-08	9.42 E-04	1.72 E-03	54.7%	0.00%
	Methane (CH4)	1.22 E-06	2.15 E+02	5.68 E-09	4.89 E-04		28.4%	
	Carbon dioxide, fossil (CO_2)	6.89 E-07	2.15 E+02	3.21 E-09	2.76 E-04		16%	
Minerals	Nickel, (Ni)	2.06 E+00	2.88 E-03	7.16 E+02	4.12 E+02	6.10 E+02	67.6%	7.92%
	Copper, (Cu)	1.13 E-01	2.88 E-03	3.92 E+01	2.26 E+01		3.7%	
	Zinc (Zn)	1.01 E-01	2.88 E-03	3.52 E+01	2.03 E+01		3.3%	
Eco-toxicity	Zinc (Zn)	2.08 E+02	1.78 E-04	1.17 E+06	4.16 E+03	4.18 E+03	99.5%	76.16%
	Zinc in the air (Zn)	5.29 E-01	1.78 E-04	2.97 E+03	1.06 E+01		0.25%	
	Nickel (Ni)	3.17 E-01	1.78E -04	1.78 E+03	6.35 E+00		0.15%	
Acidification/ Eutrophication	Nitrogen oxide (NO)	3.83 E+00	1.78 E-04	2.15 E+04	7.66 E+02	8.58 E+02	89.3%	15.55%
	Sulfur dioxide (SO2)	3.05 E-01	1.78 E-04	1.71 E+03	6.10 E+01		7.1%	
	Sulfur oxides (SOx)	1.31 E-01	1.78 E-04	7.35 E+02	2.62 E+01		3.1%	
Land use	N/A	N/A	1.78 E-04	X	X	X	X	X
Radiation	N/A	N/A	2.15 E+02	X	X	X	X	X
Ozone layer	N/A	N/A	2.15 E+02	X	X	X	X	X

5.2.4. Conclusion

The relative performances of the cork composite and GFRP among impact categories are summarized in the table below, where differences are expressed as a relation to core material with the best performance.

Table 5-10: Relative impact of the different core material studied

Impact categories	**Type of core materials**	
	Cork composite	**GFRP**
Carcinogen	1.00	4.11
Resp. organics	1.00	4.81
Resp. inorganics	1.00	6.67
Climate change	1.16	1
Minerals	1.00	6.24
Ecotoxicity	1.00	1177.92
Acidification/Eutrophication	1.00	62.99

Considering that in this study, we assumed the environmental benefit of the cork composite over GFRP, this result applicable for the comparison of the environmental performance of the cork composite and GFRP.

Chapter 6 Conclusion

The goal of this study is to develop a new core material offering competitive functional performance with economic and environmental benefit. Cork–based plastic composite is developed since it is assumed that cork properties such as low density, water-tightness, fire resistance, and elasticity could be introduced into the core part where those properties are desired.

The first design requirements that we should meet is to check whether the cork composite possesses appropriate level of strength and modulus because its ultimate application will be mostly in structural area. Therefore, several mechanical testing are conducted to determine its mechanical properties and results are compared with those of GFRP to see its relative performance. It is turned out that there still exists room for improvement to reach certain level of functional performance as a structural material. However, the specific properties of the cork composite are comparatively high since the cork composite is three times lighter than GFRP.

Since economic benefit is an important matter of interest, the costs for manufacturing of classic core materials including phenolic resin coated honeycomb, PET foam, GFRP and the cork composite are calculated. The most expensive core material for having the same functional performance is honeycomb and the cork composite takes second lowest price.

Eco-impact has not been necessarily considered as an important factor of choosing material for product or system. However, utilizing environmentally harmful materials turns out to affects significantly not only environments but also human health, eco-impact should be carefully reviewed. Life Cycle Assessment on the cork composite and GFRP is evaluated using eco-indicator 99 method. The climate change induced by using the cork composite and GFRP approximately similar while the cork composite has much less environmental impact on other impact categories

We have evaluated how newly developed cork-based plastic composite material satisfies its intended goal by examining its functional performance, economic benefit and eco-impact. The basic capability of the cork composite as a core material is proved with economic and environmental benefit

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