Flexural Analysis of Rubberized Concrete Beams using Finite Element Method

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Abstract

The amount in consumption of rubber and its waste production has been rapidly growing which can be a serious threat to the natural environment. Waste tires are largest sources of global waste rubbers production, due to the rapid increase of human population. Disposal of rubber wastes and used tires is one of the biggest challenges for every country in the 21st century.

The objective of the thesis is to recycle rubber tire waste in producing rubberized concrete by partially replacing mineral aggregates (mixture of sand and gravel). In this study, the effects of percentage variation of rubber as mineral aggregates in concrete were studied, in terms of its behaviour under flexural load. This thesis deals mainly with the theoretical approach to analyse the flexural behaviour of rubberized concrete. This thesis also presents the previous related studies to determine the actual effect of rubbers in flexural properties of concrete. In addition, COMSOL Multiphysics software was used to do finite element analysis of rubberized concrete beams. The concrete beams containing different replacement percentages of rubbers (0%,5%,10% and 15%) were modelled and analysed in COMSOL Multiphysics. The study results showed that incorporating rubber as replaced rubber aggregates can cause significant effect on the flexural behaviour of concrete. It was found out that rubberized concrete has higher ductility, deformation and energy absorption capacity but has relatively lower flexural strength than the normal concrete.

Keywords:	Rubber, Waste tire, COMSOL Multiphysics, Finite Element Analysis, Rubberized Concrete
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FOREWORD

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Sagar Gurung

1 INTRODUCTION

1.1 Background

Rubber is one the greatest inventions in the history of human civilization. Rubbers were first produced from natural sources i.e. rubber tree. Those rubbers were crumby, water-soluble, sticky, and smelly in nature due to which they were not applicable to use for industrial purposes. These undesirable qualities of rubber were upgraded in 1839 when vulcanization process was introduced by Charles Goodyear. Vulcanization process is the greatest discovery in the field of rubber technology. Today, rubbers are used in producing varieties of products varying from household items to medical and industrial products. [1]

According to the data from survey performed by the rubber industry, the global consumption of rubber was about 17 million tons per year in 2000. [2] According to a research data published by the International Research Group, the consumption of the total rubber is estimated to be increased by 3.4% to 29 million tons in 2018 and by 2.5% to 30.12 million tons in 2019. The data also shows that the number of waste rubbers production is estimated to be more than 1.5 billion. [3] Both natural and synthetic rubbers are used in the production of various rubber goods. Figure 1 illustrates the statistical report on the percentage of production and consumption of both natural and synthetic rubber in the world.

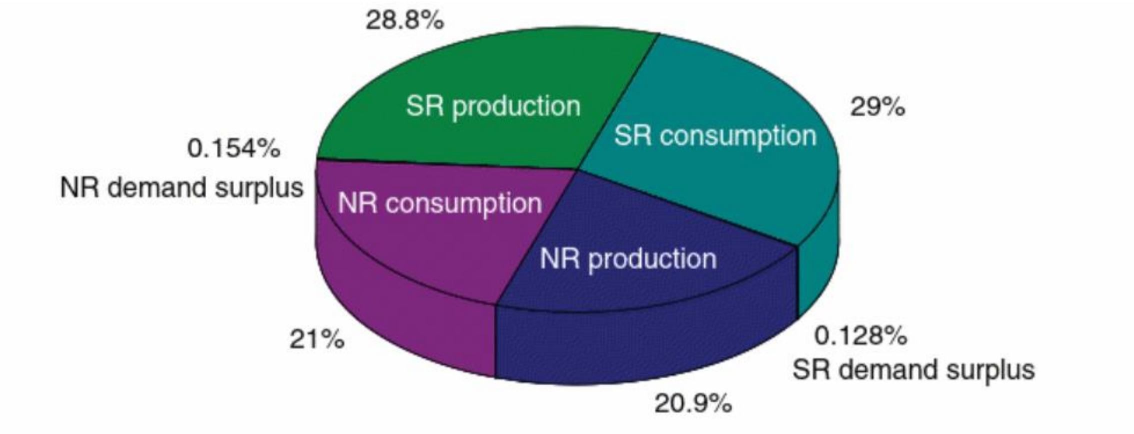

Figure 1:Production and Consumption of Natural Rubber (NR) and Synthetic Rubber (SR) in the World [4]

Rubber goods can be classified into two different sectors- the tire sectors and the general rubber goods (GRG). Tires are the most important parts in every vehicle such as car, trucks, bicycles, aircrafts and so on. Tire industries have been rapidly increasing world-wide. Because of this, huge quantities of tires are discarded every year. It is estimated that more than 1 billion waste tires are generated annually all over the world. European tire & rubber manufacturers' association describes waste tires as end-of-life tires (ELTs) which means they cannot be used for their original purpose and directly go into the waste management system for recovery. [5]

All those waste rubber goods and tires are non-biodegradable and hard to recycle due to which the most common methods to dispose their wastes are landfills, stockpiling and Incineration. These types of disposal systems will cause a great impact in the environment and the life of human beings. So, it is important and worthwhile to find out a suitable, cost effective and eco-friendly way to reuse or recycle those waste materials.

With the rapid population growth, people continue to put a great demand on global natural resources which leads in depletion of resources and biodiversity. In order to protect the world from resources crisis and ensure the well-being of future generations by reducing the consumption of naturals resources, it is necessary to use the material resources accumulated in the waste. Rubber wastes can be valuable raw material resources if they are properly recycled.

Concrete is mixture of cement, water, coarse aggregates and fine aggregates. Concrete is the most used construction material in the world. According to the European Ready Mixed Concrete Organization statistics (ERMCO), it was found that the annual production of concrete in the world is about 5 billion tones. [6] The aggregates which are used in making the concrete are produced from natural resources. Thus, high demand of concrete production leads in shortage of aggregate minerals in nature. From an ecological point of view, waste rubber tire can be the best substitute for concrete components to replace the fine or coarse aggregates in concrete.

Because of nature of rubber like ductility, good strength and strain control properties, Civil engineers are more attracted in rubberized concrete production for the construction industry in recent years. Adding rubber to concrete not only helps in controlling the waste rubber amounts and consumption of natural resources but also improves certain properties of concrete. Currently, the use of rubber particles in the concrete industry is low and is gaining more popularity among engineers and scientists for the concrete aggregates replacement.

1.2 Aims of thesis

The purpose of the study is to develop a new reinforced concrete using waste rubber particles as replacement of concrete mineral aggregates and thereby to discover a suitable solution to the existing problem of disposing the waste rubber and tires produced and accumulated in large quantities.

The summary of the main objectives of this project are listed below:

- To perform the theoretical analysis of the flexural properties of the concrete containing rubber particles as replaced mineral aggregates.
- To analyze the flexural behavior of rubberized concrete beam using Finite element method (FEM).
- To investigate and evaluate the performance of rubber modified concrete by comparing with the normal concrete having no replacement material and identify the appropriate amount or volume of rubber content in concrete mix for producing a good quality of final concrete product.
- To determine whether the rubberized concrete is more workable and useful for construction.
- To promote the practical use and acceptance of recycling waste materials in production of various useful products in order to preserve natural minerals and protect the environment.

2 LITERATURE REVIEW

2.1 Rubbers in general

Rubber can be simply defined as a material that deforms with a comparatively low load/deflection ratio when subjected to an external force and recovers its original shape quickly and forcibly when forces applied to it are withdrawn. It is a unique material because it can adopt both elastic and viscous property. [7]

Types of Rubber

Rubber is divided into types based on its origin – Natural Rubber and Synthetic Rubber.

2.1.1 Natural Rubber

Natural rubber is also known cis-1, 4-polyisoprene. NR is basically a hydrocarbon which is a polymer of Isoprene (C5H8), built up by joining the monomers of isoprene in the form of a continuous chain. The molecular weight of rubber ranges from 1 to 2.5×10^6. [8]. It is produced by enzymatic processes. It is extracted from the bark of Hevea Brasiliensis tree in the form of latex. Latex is milky white liquid which can be obtained by process called tapping. Fresh latex contains about 35-40% rubber. [9]

2.1.2 Synthetic Rubber

Synthetic rubber is one of the types of rubber which is produced artificially on an industrial scale. They are synthesized from raw materials which are derived from petroleum, coal, oil, acetylene and natural gas. They are manufactured on an industrial scale in solution, suspension, or emulsion polymerization methods by copolymerizing two different polymers. This artificial elastomer has similar or even better properties than natural rubber. [9]

2.1.3 Types of Synthetic Rubber

There are different types of synthetic rubbers found around world. They have different chemical and mechanical properties that make them suitable for different applications. Some of the popular and useful synthetic rubbers are listed below.

Table 1: Types of Synthetic rubber [8]

Rubber Types	Properties	Applications
SBR **(Styrene butadiene rubber)**	Stress-cracking resistance, abrasion resistance, thermal resistance, aging resistance	Tires, rubber hoses, wire clothing, adhesive tapes, etc.
CR **(Neoprene or Chloroprene)**	Good mechanical and electrical properties, very good resistance to chemicals, ozone, aging and heat	Car radiator hose, gaskets, wire clothing, waterproof rubber, etc.
BR **(Butadiene polybutadiene)**	High resilience, good low-temperature properties, cold and abrasion resistance	Soles of shoe, Tires of airplane, rubber rolls, etc.
NBR **(Nitrile isoprene rubber)**	Excellent oil and alcohol resistance, poor cold resistance, moderate mechanical properties, abrasion resistance	Oil hoses and caps, conveyor belts, print rolls, etc.
EPDM **(Ethylene propylene copolymer and terpolymer)**	Good resilience and mechanical properties, excellent resistance to oxidation, ozone, chemicals, weathering and high temperatures.	Conveyor belts, hoses, wire clothing, etc.

2.1.4 Vulcanization of Rubber

Vulcanization is a chemical process that is used to harden rubber to produce most useful articles, such as tire. Unvulcanized rubber behaves like thermoplastic and does not retract basically to its initial shape after a large deformation. Therefore, vulcanization can be as the curing process in which rubber is heated with sulfur at high pressure in order to increase the rubber's strength and durability. This results in the formation of crosslinks between rubber molecules. Cross-linking improves the elasticity, viscosity, resilience and aging properties of rubber. Due to vulcanization, rubber become insoluble in solvent and show excellent resistance to heat and light. It also produces very strong and rigid rubber that is far better than raw rubber. [10]

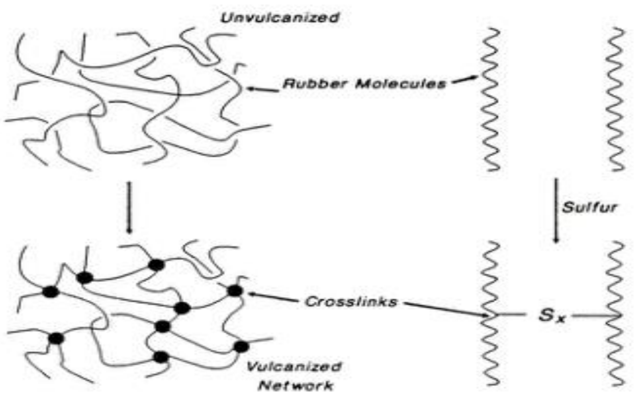

Figure 2:Vulcanization of rubber [10]

2.1.5 Rubber Recycling Methods

Rubber recycling is an eco-friendly and economical method to reduce the rubber wastes. Recycling of rubber wastes help to produce cheaper and better rubber products than those produced from natural raw materials. There are basically three ways to recycle rubber wastes: (1) they can be burnt by combustion process to produce energy, (2) they can be converted into crumb rubber to produce different kinds of products, or (3) they can be recycled into its original form by using devulcanization process. Recycling of rubber should emphasize more in recovery of raw materials from waste products rather than in recovery of energy because energy-recovery method is expensive and produces relatively huge amount of pollution in the environment. [11]

Table 2: Rubber Recycling Method [11]

Types of Recycling		**Recycling Method**
Reuse of Waste Rubber	Repairing	Retreading
Material Recycling	Physical Process	Cutting Shredding Processing to crumb and ground rubber
	Chemical Process	Reclamation Devulcanization
Energy Recovery from Waste Rubber	Thermal Process	Incineration Pyrolysis

2.2 Concrete Technology

Concrete can be simply defined as a composite material that consists of fine and coarse aggregates bonded together by cement and water. Following equation shows the formula to produce concrete using its ingredients.

$$Cement\ (9-15\%) + Water(15-16\%) + Admixture = Cement\ Paste$$
$$Cement\ Paste + Fine\ Aggregates\ (25-30\%) = Mortar$$
$$Mortar + Coarse\ Aggregates\ (30-45\%) = Concrete \tag{1}$$

Concrete is flowable like liquid in its fresh state, so it can be poured into various frameworks to produce different sizes and shapes of concrete like rectangular, square etc. When it gets hardened, it becomes strong and durable. It is used to construct many different structures such as dams, pavements, bridges, buildings, and much more than any other construction materials. Its worldwide production is 30 times that of steel by volume. This is due to its low-cost production rate and availability of its raw materials in every corner of the world. [12]

2.2.1 Cement

Cement produces cement paste when mixed with water. Cement paste coats the surface of course and fine aggregates and binds them together to form a durable rock-like mass known as concrete. Hardened concrete can be formed only when the paste gets hardened. The hardening of cement paste is due to the chemical reaction known as hydration.
Cements used in construction are generally inorganic, made from different natural minerals. Portland cement is the most popular and widely used cement for construction. It is a mixture of Portland cement clinker and a small amount of gypsum (about 3-7%). It is produced through blending of a proper mixture of clay and limestone at high temperature of about 1450 ^{o}C in cement rotatory kilns. [12]

Compounds of Cement: The major compounds of ordinary Portland cement are tricalcium silicate (C_3S), Dicalcium silicate (C_2S), Tricalcium aluminate (C_3A), and Tetracalcium aluminoferrite (C_4AF). These compounds form chemical bonds with water molecules when cement is mixed with water. As a result, each compound undergoes hydration reaction to produce hardened concrete. The properties of both cement paste as well as concrete depend upon the functions of these compounds in hydration. Table 3 illustrates the major compounds of the cement with their function in concrete production. [13]

Table 3:Function of cement compounds in hydration [13]

Chemical Formula	Oxide Formula	Shorthand Notation	Description	Typical Percentage	Mineral Function
Ca_3SiO_5	$(CaO)_3SiO_2$	C_3S	Tricalcium silicate (alite)	50–70	Hydrates quickly and imparts early strength and set.
Ca_2SiO_4	$(CaO)_2SiO_2$	C_2A	Dicalcium silicate	10–30	Hydrates slowly and imports long-term (ages beyond 1 week) strength.
$Ca_3A1_2O_6$	$(CaO)_3A1_2O_3$	C_4AF	Tricalcium aluminate	3–13	Hydrates almost instantaneously and very exothermically. Contributes to early strength and set.
$Ca_4A1_2Fe_2O_{10}$	$(CaO)_4A1_2O_3Fe_2O_3$	C_4AF	Tetracalcium aluminoferrite	5–15	Hydrates quickly. Acts as a flux in clinker manufacture. Imparts gray color.
$CaSO_4 2H_2O$	$(CaO)(SO)_3(H_2O)_2$	$C\bar{S}H_2$	Calcium sulfate dehydrate (gypsum)	3–7	Interground with clinker to make Portland cement. Can substitute anhydrite ($C\bar{S}$). Controls early set.
$CaSO_4$	$(CaO)(SO_3)$	$C\bar{S}$	Anhydrous calcium sulfate	0.2–2	

2.2.2 Fine and Coarse Aggregates

About 80% of total volume of concrete is occupied by aggregate. Concrete mixture proportions and concrete economy are greatly influenced by aggregate. Aggregate has significant impact in the properties of fresh concrete such as fluidity, cohesiveness and rheological behavior. Similarly, it also affects the properties of hardened concrete such as its strength, weight, bond, shrinkage and wear resistance.

According to the origin of aggregates, they are classified into natural and synthetic aggregates. Natural aggregates are obtained from natural deposits in the form of crushed or uncrushed state such as sand and gravel or stone. The sources of natural aggregates are riverbeds, lake, rocks, etc. Synthetic aggregates are derived from products or by-products of industry such as blast furnace slag and waste rubber products. Based upon the size of aggregates, they are divided into two groups: Fine and Coarse aggregate. The size of the coarse aggregate ranges from 5 mm to150 mm whereas the size of the fine aggregate is less than 5 mm. [12]

2.2.3 Water

Water is responsible for the hydration of cement. It is very important to determine the appropriate amount of water to make cement paste because the quality of cement paste has great impact in determining the character of concrete. The increase of water amount in cement paste results in the production of low-quality concrete and affects the setting time and workability of the concrete. This is because if more water is added in concrete then the binding power of the cement decreases that causes greater spacing between the aggregates in cement. As a result, voids are developed in such empty spaces that can be responsible for the reduction of concrete strength. The minimum ratio of water to Portland cement ranges from 0.36 to 0.42. However, if the content of cement in cement paste is too much than that of water, then it results in the too fast drying and shrinking of concrete. The water used to make concrete should be clean and free from various impurities like waste, acid, oil, etc. These impurities can hinder the hydration reaction of cement paste. Generally, drinking water is used for mixing the concrete [12]

2.2.4 Admixtures

Admixtures are used as ingredients in concrete in the form of liquid, powder or paste. The main purpose of using admixture is to enhance the properties of both wet and dry concrete by physical or chemical processes. They are also used to create cheaper and eco-friendly concrete. They are mostly applied to the concrete before or during mixing. They should be utilized in small quantity so that they should not affect the mass or volume of the concrete mix. For instance, Water-reducing admixtures are used to reduce the amount of water content required to produce concrete mix. Similarly, accelerator admixture is used to speed up the curing and hardening process of the concrete. [12]

2.2.5 Mix Design

The mix design of concrete can be defined as the processes of selecting suitable ingredients for concrete such as water, cement, aggregates and admixtures, and determining their right quantities in order to construct a concrete of desired properties in both hardened and fresh states.. Mix design is very important in concrete construction as it helps in producing better quality of concrete. This also facilitates in producing economical concrete mix and avoids the failure of mixture. It also helps to save valuable time and efforts during construction of concrete mix. There are various methods to design the concrete mix and can be varied for every country. Concrete mix design is based on empirical relationships, tables, graphs and charts created from experimental investigations and construction data. For example, table 4 shows the concrete mix proportions for different grades of concrete according to IS456:2000 method. [14]

Table 4: Mix design of Concrete according to IS456:2000 [14]

Grade of Concrete	Mix Ratio	Compressive Strength (N/mm^2)
M10	1:3:6	3.5
M20	1:1.5:3	4.0
M30	Design Mix	5.0
M40	Design Mix	5.0

2.2.6 Compacting and Finishing

Concrete should be properly compacted after it is placed into framework. When concrete is deposited into frameworks, air bubbles can develop in concrete and occupy about 5-20% of the concrete total volume. Hence, the reason for compacting the concrete is to avoid the air entrapped in concrete and to fill all the spaces of frameworks including every corners and gaps with concrete mix. Proper compaction helps to produce denser and stiffer concrete. High-quality of concrete with better strength can be only possible if compaction of concrete is done properly.

Good finishing must be performed on the fresh concrete by using trowel. Good finishing helps to create a smooth surface on the concrete structure and make the surface layer more compact, denser and properly graded in order to avoid water evaporation and increase water resistance. [14]

2.2.7 Transition Zone

In freshly compacted concrete, water films develop in the vicinity of coarse aggregate particles. Due to this, higher water/cement ratio and fewer cement particles existed closer to the larger aggregates compared to the region away from the aggregates. This leads to the formation of microstructure of hydrated cement paste around the aggregates that is different from the normal cement paste. Such zone around those aggregates is called third phase or popularly known as transition zone in concrete technology. It can be simply defined as interfacial zone between coarse aggregate particles and the hydrated cement paste (see fig.3). It forms as thick shell, usually 10-50 µm thick around the large aggregate. This third phase occupies only a tiny fraction of the total volume of concrete, but it significantly affects both physical and mechanical properties of concrete. This is also known as the weakest link of the concrete. Due to the presence of transition zone in concrete, concrete is relatively tough in compression but weak in tension. [14]

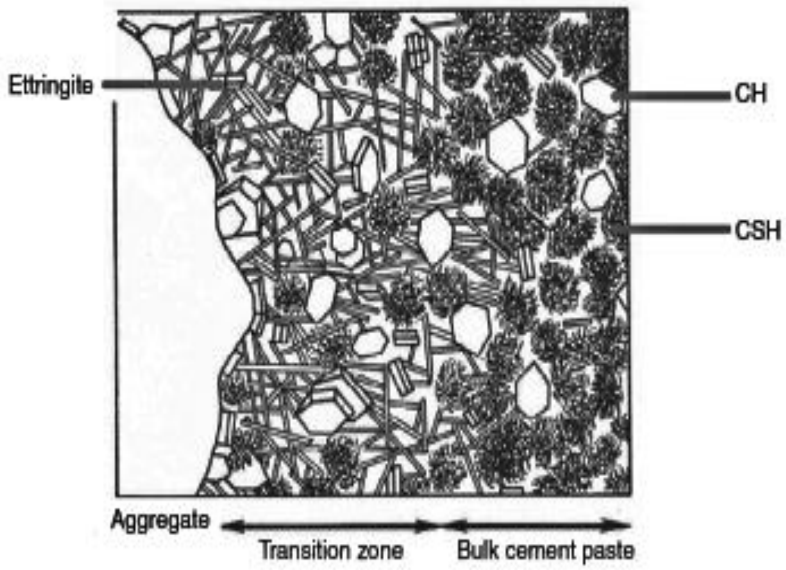

Figure 3:Interfacial zone of concrete [14]

2.2.8 Curing of Concrete

Curing is the process in which the concrete is kept in favorable moist condition under recommended temperature range to protect it against the loss of moisture due to the hydration reaction and atmospheric temperature. Curing should be performed after the initial setting time of concrete. [12]

During the fresh state, concrete usually has enough water for processing hydration reaction. But when it starts to harden slowly, the concrete begins to lose water in excessive amount. As a result, it makes concrete dry and retards hydration reaction that can cause defects in its microstructure and develop unstable dimension of concrete. Such problem in concrete can be avoided by properly placing concrete in water. Proper curing helps to improve strength and reduce cracking in concrete. The minimum time period for curing of Portland cement concrete is 7 days. [14]

2.2.9 Shrinkage in Concrete

Shrinkage of concrete can be defined as the change in volume of concrete in hardened state due to loss of moisture from the surface of concrete by evaporation. There are many factors which can influence shrinkage of concrete which are mentioned in above sections. The best way to reduce shrinkage in concrete is by curing the concrete in moist conditions for specific period after its initial setting (no less than 7 days). Usually, the rate of shrinkage is high during the initial stage of hardening and the rate slowly reduces with time. Shrinkage is one of the main causes for cracks in concrete. Due to shrinkage, the deflection of concrete structure increases over time. It reduces the long-term strength and durability of the concrete. [15]

2.2.10 Creep in Concrete

When concrete is subjected to sustained load, it undergoes both elastic and plastic deformation. Beyond the elastic limit, the plastic deformation of concrete continues to increase with time even though the stress level is not altered. Such plastic deformation or time-dependent deformation under constant stress is known as creep. Creep increases with increase in loading stress and loading rate. At the beginning creep develops rapidly in the concrete but it slowly decreases with time. Creep mostly develops around the aggregate region in hardened concrete mix. Creep takes place in compression, tension, bending and torsion of concrete. Development of creep is disadvantageous for concrete structure as it can cause excessive deflection and creates crack in concrete structure. [15]

2.2.11 Strengths of hardened concrete

Strength of any material depends upon two terms: Stress and Strain. So, it is very important to know what stress and strain is. As stress can be defined as the force per unit original cross-section area of a material. It can be expressed as: [12]

$$\sigma = \frac{F}{A} \tag{2}$$

Where $\sigma = Stress$; F = applied force; and A = Cross sectional area of the material. The SI unit of stress is Pa or Nm-2.

Strain can be defined as the change in length per unit original length of a material. It is given as: [12]

$$\varepsilon = \frac{\Delta L}{L_O} \tag{3}$$

Where $\Delta L = Change\ of\ the\ length$; and $L_O = Orginal\ length.$

Strength of a concrete is defined as the ability of the concrete to withstand the stress applied by an external force without failure. It is easy to identify the failure in concrete by the appearance of cracks. Different types of forces such as compressive, tensile, flexural, shear or torsion forces can be applied on concrete to generate stress to determine the strength as property of the concrete. A universal testing machine is used to conduct various tests for the measurement of different strengths of concrete [15]

2.2.12 Compressive Strength of Concrete

Compressive strength of concrete is one of the most important properties of hardened concrete. It is also known as the ability of concrete to withstand loads which tend to compress it. Compressive strength testing is the mostly used method for engineers to calculate the strength of any concrete while designing structures. Compressive strength of any concrete is measured by breaking cylindrical or cubic concrete specimens in a compression testing machine. Results obtained from compressive strength tests are used for different purposes such as for quality control, acceptance of concrete, for estimating the strength in concrete, or evaluating the adequacy of curing and protection afforded to structure. It is estimated that the compressive strength of concrete is ten times the tensile strength of it. [14]

2.2.13 Tensile Strength of Concrete

Tensile strength of concrete is another important property of concrete due to which it resists the pulling force or tensile stress. Concrete is brittle in nature, and it cannot withstand high tensile stresses. This is the reason why the tensile strength of concrete is much lower when compared with its compressive strength.

Direct tension testing of concrete is difficult to perform, and the results obtained from the test is not reliable for determining its tensile strength. Due to this, indirect test methods are mostly used to determine the tensile strength of concrete which are: Split Tensile Testing and Flexural Testing. [12] In the following section, flexural testing method is only discussed as the aim of the thesis is to determine the flexural behavior of concrete.

2.2.14 Flexural Testing

Flexural strength testing is one of the indirect testing methods to determine the tensile strength of concrete. It measures the ability of concrete to resist the maximum tensile stress applied on its tension zone at the point of failure in bending. The flexural strength is also called as Modulus of Rapture (MR). Engineers usually do not use this method for quality testing of the concrete as they see this testing method as less convenient and unreliable. [14]

Flexural strength of concrete can be determined by performing three-point or four-point bending test as shown in figure 4. Both flexure testing methods are very similar to each other. However, the major difference between them is that the load is applied in the center of the sample through a single point in three-point bending test, whereas in four-point bending test the load is applied through two points on top of the sample as shown in fig.4 (b). [16] Four-point bending test is more suitable for determining the flexural strength of concrete because the concrete cannot withstand shear stresses very well.

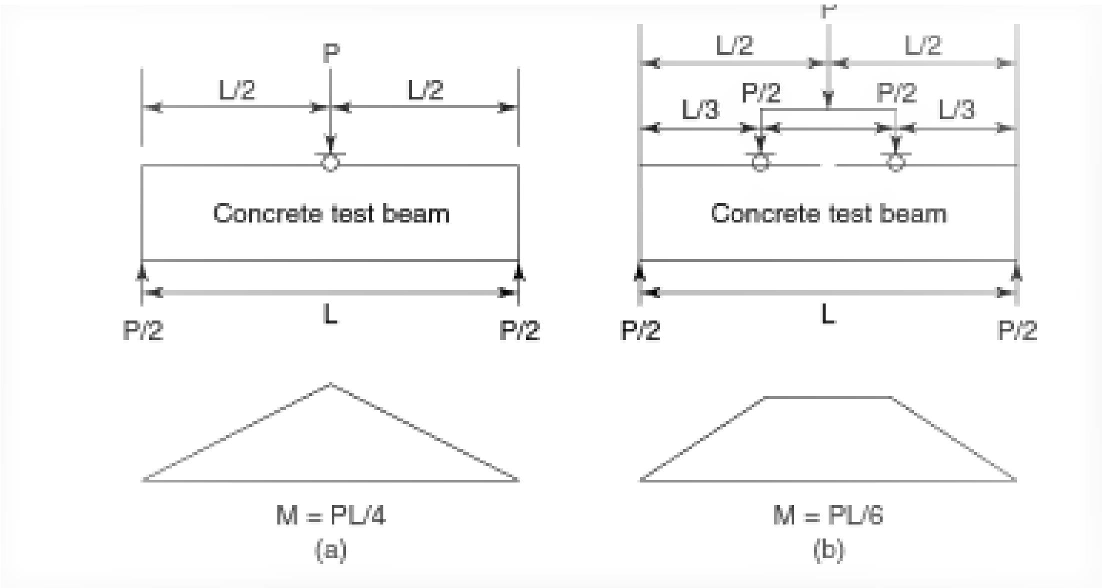

Figure 4:Flexural Testing (a)three-point loading, (b)four-point loading [14]

In four-point bending test, if the fracture takes place within the middle 1/3 portion of the span length, the flexural strength of concrete specimen can be computed as:

$$R = \frac{PL}{bd^2} \tag{4}$$

Where, P is maximum load, L is span length, b is specimen length and d is specimen depth. [14]

Fracture mainly occurs within the middle 1/3 portion of the span length of the sample. However, the fracture can occur outside the middle one-third which indicates that the cross section carries both bending moment and shear force. The results of fracture outside the middle one-third are usually discarded for the flexural strength test. However, ASTM allows to use such as result. [12] The following formula is applied to calculate the modulus of rupture (MOR) of the concrete specimen when the fracture occurs outside the middle 1/3 portion of the span length of concrete specimen.

$$R = \frac{3Pa}{bd^2} \tag{5}$$

Where a is the distance from the nearest support. [14]

2.2.15 Reinforced Concrete

Reinforced concrete is a special type of concrete in which reinforcement is provided in order to provide necessary tensile strength to concrete. For the reinforcement, materials with having higher tensile strength should be embedded in concrete during concrete mixing. Those materials can be steel reinforcing bars, polymers and so on. When those materials are placed in concrete mix, they form a strong bond together and act effectively as a single structural element. Those materials inside the concrete provide reinforcement to concrete to resist the stresses produced due to the external applied load. Reinforced concrete is very popular and widely used economical construction material around the world. Reinforced concrete has relatively high tensile strength and is more durable than unreinforced concrete. Reinforced concrete are widely used for building various types of structures such as dams, bridges, buildings, footings and so on. [15]

2.3 What is tire?

A tire is a ring or circular shaped rubber component attached to the rim of a wheel. It has inner rubber tube which is filled with compressed air. The tire with the help of inner tube supports the whole weight of the vehicle. When a tire of a vehicle comes in contact with road surface, it provides traction on the surface for the smooth movement of the vehicle. There are various types of tires found in the global market. Those types of tires are classified based on the types of vehicles they serve such as bike tires, car tires, aircraft tires etc. [10]

2.3.1 Tire Composition

Tire consist of several components, each of which has specific function in performance of tire. (see fig. 5) Those tire components are made from different raw materials. About 200 raw materials are used to make a tire. The main material used in tires is rubber. Other different types of chemicals such as carbon black, fillers, vulcanizing agents, accelerators etc. including steel and fabric are added to tires for reinforcement. [17]

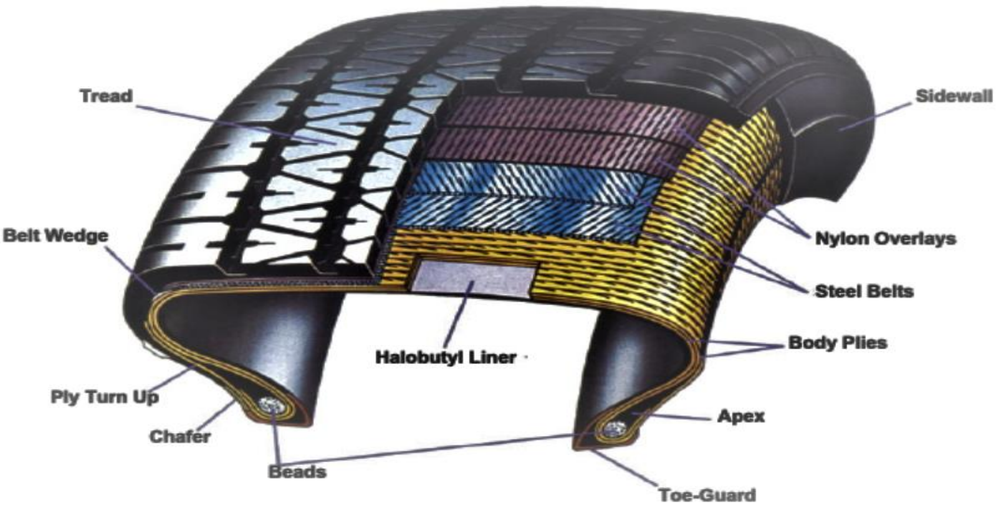

Figure 5:Components of a tire [10]

Table 4: Composition of tire (in weights) [17]

Materials	Passenger Cars	Truck tires
Natural Rubber	19%	34%
Synthetic Polymers	24%	11%
Fillers	26%	24%
Antioxidants, Antiozonants, Curing systems	14%	10%
Textile	4%	0%
Steel	12%	21%

2.3.2 Waste Tire Problem

About two-thirds of the total rubbers produced in the world are used in manufacturing of tire. The composition of tires makes them extremely difficult for recycling. They do not degrade naturally. Discarded tires in landfills can be the best place for mosquitoes, snakes, and other harmful animals for breeding. They occupy large space in landfills. They can leach hazardous chemicals to soil and water. They can create fire hazard and may produce toxic fumes when they are burnt. [10]

At the present situation, many countries are using highly polluting recycling method to recycle waste tires i.e. burning of waste tires to produce fuel oil. Tire waste management in Europe during 2015 is presented in figure 6. Still in many developing countries, enormous amount of tire waste ends up in landfills due to poor economy. For such countries, recycling tire in concrete can be the best solution. This recycling method is comparatively simple, economical and eco-friendly than other tire recycling methods.

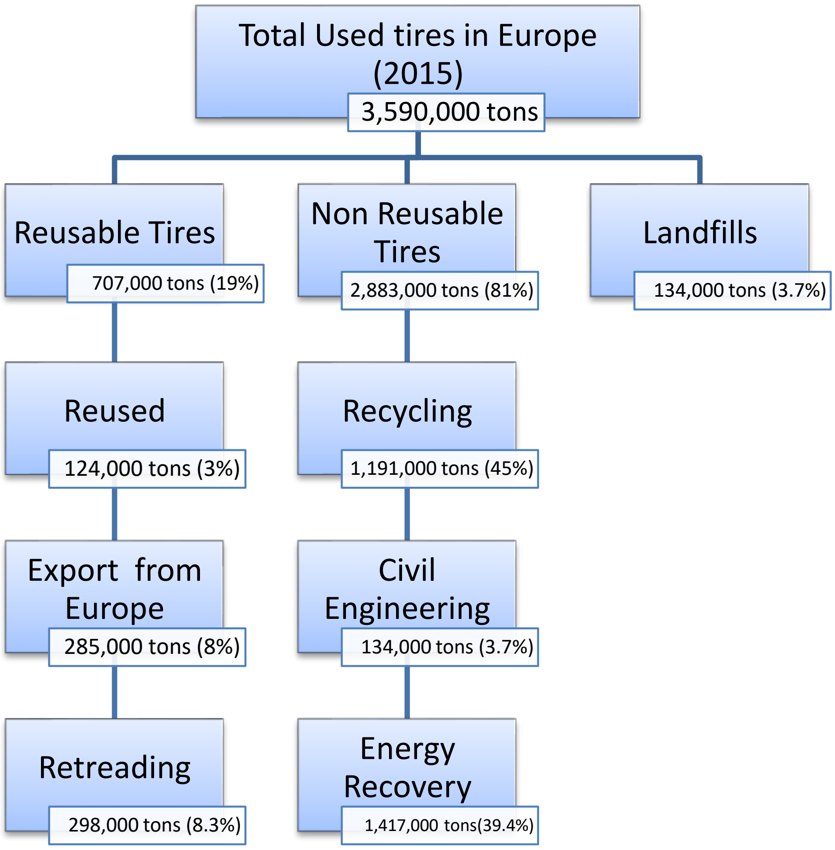

Figure 6:Waste Tire Management in Europe [18]

2.3.3 Crumb Rubber

Rubber grinding process is used to remove reinforcing textiles, metal or other impurities from the rubbers and make them into a suitable particle size rubber known as crumb rubber. There are several methods to reduce tire rubber into small particle sizes. Among those methods, Ambient grinding and Cryogenic grinding are the most used method. The size of crumb rubber is in the range of 0.425-2.45 mm. Crumb rubber is also known as recycled rubber which has a wide range of applications. Crumb rubbers are mostly used as concrete materials to produce various concrete structures. [19]

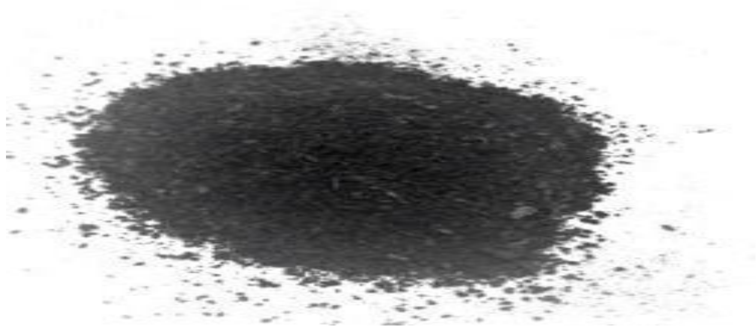

Figure 7:Crumb Rubber

2.3.4 Bonding between Rubber and Cement paste

Rubbers are hydrophobic in nature that means the interfacial bonding between the rubber particles and the cement paste is weak. When concrete containing rubbers undergoes hydration reaction, rubber aggregates tend to repel the cement paste causing the existence of thicker water film around the aggregate surface. This can lead to the formation of wide and porous Interfacial Transition Zone between rubber particles and cement paste indicating weak bonding between them. As a result, huge number of micro cracks can develop near that zone at hardened stage of concrete which can cause reduction in its strength characteristics. Bonding between them also depends upon the percentage, size and the surface texture of the rubber aggregates. [20]

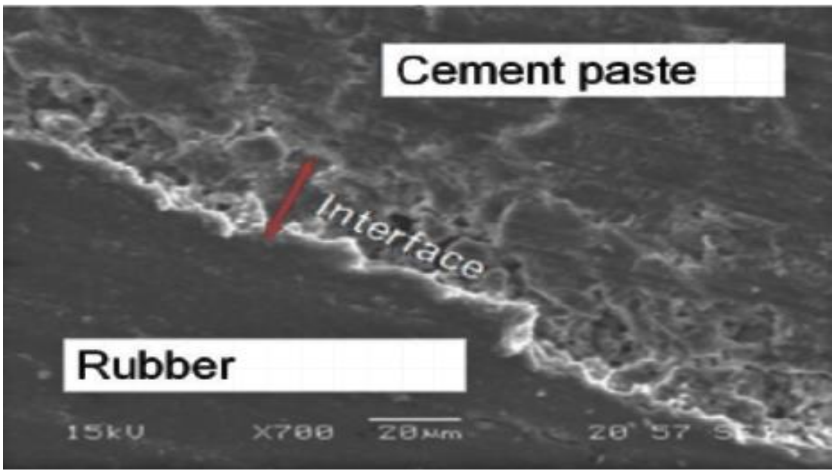

Figure 8:ITZ between Rubber and Cement paste [20]

2.3.5 Elastic Properties of Rubber

Rubber behaves like incompressible substance because its volume does not change under applied compressive load. Rubber can sustain large deformation of as much as of 1000 percent and has ability to return to its original dimension after such deformation. It has Poisson's ratio of about 0.5. The modulus of elasticity of rubber is low. The stress-strain relation for rubber is only proportional at very low strains as shown in stress-strain graph of rubber in figure.13. Due to this, rubber exhibits highly non elastic behavior. [21]When rubber is subjected to loading, it absorbs more energy on loading compared to the energy it releases on unloading. This is due to the effect of hysteresis in rubber which transfers energy to its molecules, resulting in heating. [22] This indicates that rubber has high energy absorption capacity on both tensile and compressive loading.

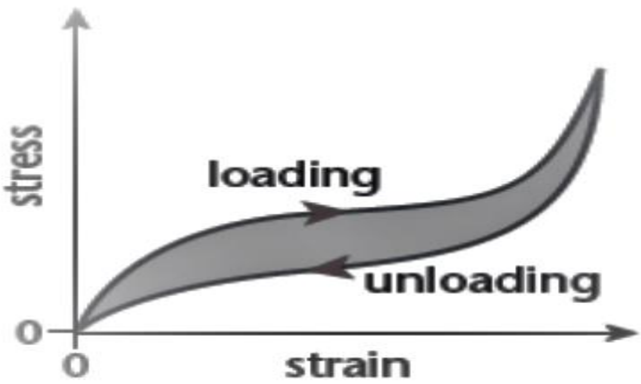

Figure 9:Stress-strain curve for rubber on loading [22]

2.4 Finite Element Analysis (FEA)

Finite element analysis (FEA) is a computerized method of modeling of products and system, for the purpose of finding and solving potential structural or performance issues. FEA is performed by using a numerical mathematic technique known as Finite element method (FEM). Engineers and scientists use this method (FEM) to mathematical model and solve complex structural, fluid and Multiphysics problems. Finite element analysis is performed by using software program coded with FEM algorithm. FEA works by generating finite element mesh that subdivides a complex structure into smaller finite elements. These finite elements contain the material and structural properties of model. Every single element of the mesh is then subjected to calculations. These calculations are thus combined to produce the overall result of the structure. [23]

2.5 Linear Elastic Analysis of rubberized concrete

Rubberized concrete is non-linear and non-elastic material. But elastic theory method is applied to analyze the flexural of the rubberized concrete beam loaded in bending when the stresses and strains are in elastic limit. Beyond the elastic limit, this theory is no more applicable, as the stress distribution throughout the beam tends to follow the strain-stress characteristics of the material. However, linear elastic analysis is popular and generally accepted as method for analyzing flexural behavior of concrete beam under design load. For the elastic analysis, assumptions should be made to determine the stress, strain, and deformation of beam induced by flexure. Those assumptions are based upon the simple bending theory which are listed below: [24]

- The beam material is assumed to be isotopic and homogeneous in each direction.
- Cement and rubber are perfectly bonded together.
- The shear stress in beam is negligible.
- Plane cross-sections remain plane even after bending of the beam.
- Stress-strain relationship of beam material is assumed to be linear.
- Concrete collapses in the extreme compression due to bending when its maximum strain reaches 0.003.

2.5.1 Theory of Flexure for Rubberized Concrete beam

A simply supported concrete beam containing rubber particles is considered for the flexural analysis of rubberized concrete for this study. When transverse loads are applied to a rubberized concrete beam, it undergoes certain deformation due to the bending moment and internal stresses produced in the beam (see fig.10) Shear force is assumed to be zero in pure bending. From the figure 10, it shows that the layers of the beam do not remain same in length after bending, as their length changes when the load is applied on the beam. The top layer of the beam contracts in its length whereas the bottom layer of the beam elongates. There is a layer in between top and bottom of the beam where there is no change in length as shown in fig 10 (b). This layer is known as neutral layer. And the line of the intersection of the neutral layer with any transverse section is called as neutral axis (N.A.) of that transverse section. [25]

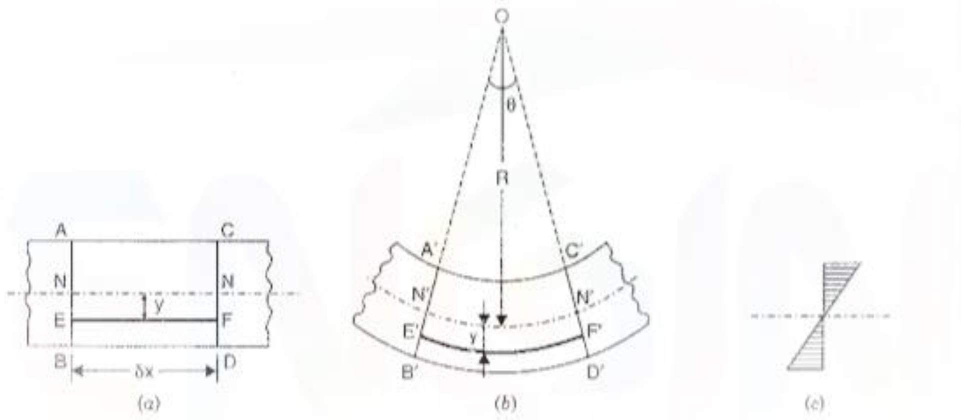

Figure 10:Pure bending of a part of rubberized concrete beam (a)beam before bending (b)beam after bending (c) Stress diagram [25]

2.5.2 Bending Equation for Flexure Theory

Consider two normal sections AB and CD of the beam, which is subjected to a pure bending, as shown in figure 10. The layer EF in the beam section is at distance y from the neutral layer NN. During bending, the longitudinal axis of the beam will deform into a curve as shown in figure 10 (b). Due to bending action, lengths of layer EF and NN will become E´F´ and N´N´ whereas section AB and CD will be A´B´ and C´D´ respectively. According to the assumption made in pure bending theory, the length of neutral layer NN will same as N´N´ (that is, NN=N´N´=δx).

Let,

$R = Radius\ of\ layer\ N'N'$

$\theta = Angle\ made\ by\ A'B'$ and C´D´ at O, which is the centre of curvature

From fig.10(b),

The strain in layer EF is given by

$$\varepsilon = \frac{Change\ in\ length}{Orginal\ length} = \frac{E'F' - EF}{EF}$$

$$= \frac{E'F' - N'N'}{N'N'} \qquad (\text{ as EF} = \text{NN and NN} = \text{N'N'})$$

$$= \frac{(R+y)\theta - R\theta}{R\theta} \qquad [\because N'N' = R \times \theta \text{ and } E'F' = (R+y)\theta]$$

$$= \frac{R\theta + y\theta - R\theta}{R\theta}$$

$$= \frac{y}{R} \tag{6}$$

Let,

$\sigma = Stress\ in\ the\ layer\ EF$

$E = Young'\ modulus\ of\ the\ beam$

According to Hook's Law,

$$E = \frac{Stress\ in\ the\ layer\ EF}{Strain\ in\ the\ layer\ EF}$$

$$= \frac{\sigma}{\frac{y}{R}} \qquad (\because Strain\ in\ the\ layer\ EF = \frac{y}{R})$$

$$\therefore \sigma = \frac{E}{R} \times y \tag{7}$$

The above equation can be written as

$$\frac{\sigma}{y} = \frac{E}{R} \tag{8}$$

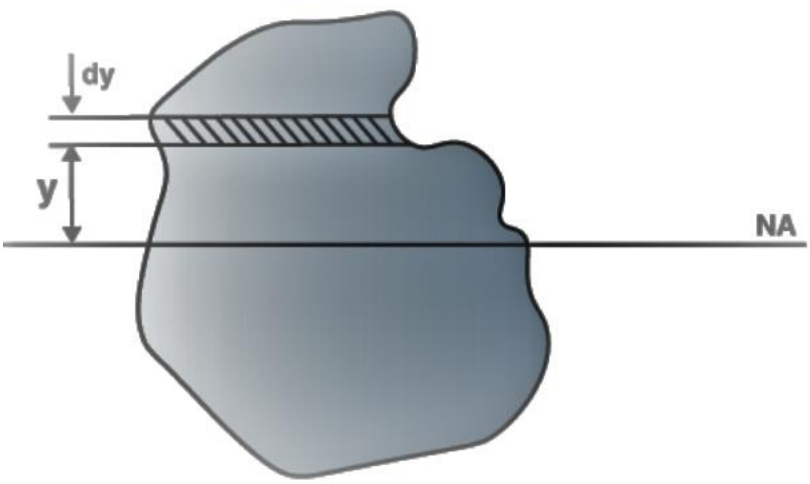

Figure 11: Arbitrary cross section of beam [26]

Consider an arbitrary cross section of beam as shown in fig.11 Let us assume an elementary strip having area dA and thickness dY at a distance y from the neutral axis.

The bending stress produced in the strip is

$$\sigma = \frac{E}{R} y \quad (eq. 7) \tag{9}$$

The force acting on the strip is

$$F = \sigma dA$$
$$= \frac{E}{R} y dA \tag{10}$$

Moment about the neutral axis is

$$dM = F \times y$$
$$= \frac{E}{R} y^2 dA \tag{11}$$

The total moment for entire cross-sectional Ares is

$$M = \int \frac{E}{R} y^2 dA$$
$$= \frac{E}{R} \int y^2 dA \tag{12}$$

Where $\int y^2 dA$ is the second moment of area of the cross-section denoted by I.

$$\therefore M = \frac{E}{R} I \tag{13}$$

From eq.7 and eq.14 we get,

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{E}{R} \tag{14}$$

Where,

I is the moment of inertia of the area of cross section, M is bending moment, σ is bending stress, y is the distance of the layer from the neutral axis, E is Young's modulus and R is the radius of curvature. [26]

Hence, This the bending equation. This equation is used by engineers to design beams and structures and to calculate their stresses and strains. This equation is used to determine the stresses produced in rubberized concrete beam due to bending moment.

2.5.3 Distribution of Strains and Stresses

During pure bending of beam, the bending stress at the neutral axis is always zero. According to the assumption in flexural theory, the normal stress at any point in a section of the beam is directly proportional to its distance from the neutral axis. The normal stress at any point above the neutral axis is always a compressive stress whereas the stress below the neutral axis is tensile stress. 'Both compressive and tensile stresses are maximum at outermost layer of the beam. Similarly, the theory also assumes that the normal strain at any point in a beam section is proportional to its distance from the neutral axis. Hence, the normal strain at any point in beam section produced due to applied bending is dependent on the normal stress at that point. This shows that the stress-strain distribution across any cross-section of the rubberized concrete beam in flexure will always be linear. Such material follows the Hooke's law i.e. Young's modulus of elasticity. The linear distribution of both strains and stresses in a beam section is shown in in figure 12. [24]

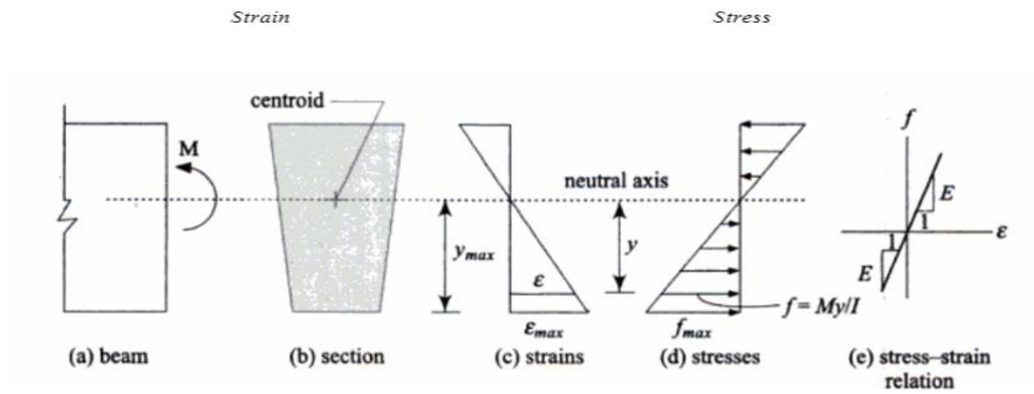

Figure 12:Elastic distribution of stress and strain in a beam section induced by flexure [24]

By applying eq.14, the normal bending or flexural stress of rubberized concrete beam caused by the bending moment can be calculated as

$$\sigma = \frac{My}{I} \tag{15}$$

Where,

σ is normal flexural stress at any point at a distance y from the neutral axis and acting on a transverse plane, M is the bending moment at the section, and I is the second moment of area inertia about the neutral axis. [24]

2.6 Flexural Behavior of Rubberized Concrete beam under load

The flexural behavior of the rubberized concrete beam under loading is discussed in this section. This includes the study of both linear and non-linear elastic behavior of the concrete beam when subjected to bending load.

When a simply supported rubberized concrete beam is subjected to loading at its midpoint, shear forces and bending moments are developed in the beam. As a result, normal stress as well as shear stresses shear are induced in the beam. Usually normal stresses are mainly considered for the analysis of concrete beam strength. In actual practice, simple bending theory does not exist. The is because the shear force acting on the loaded beam can never be zero. Longitudinal shear stresses are always produced in beam when transverse load is applied on it. [25] The flexural behavior of rubberized concrete beam at different stages of loading is described in following sections.

2.6.1 Concrete Uncracked Phase:

During this initial stage of loading, concrete beam is responsible for carrying its own weight when external load is zero. When a certain amount of increasing load is applied on the beam, it develops tensile stresses at the bottom side of the beam. Maximum stresses and bending moment occur at the midspan of the beam. At this stage, the entire concrete beam section is effective in resisting the bending moment and shear force caused by the external load. The moment developed at the middle of the beam due to increasing load is less than the cracking moment of concrete. Cracking moment is known as the moment corresponding to the tensile stress which when exceeded causes the cracking of the concrete. Similarly, the maximum tensile stresses at the bottom fiber of the concrete are less than the flexural tensile strength of the concrete. Flexural tensile strength also known as modulus of rupture. It is defined as bending tensile stress of the concrete in bending at which it starts to crack. The compressive stresses at the top fiber of the concrete are very less than the ultimate compressive stress of the beam. When the concrete reaches to its ultimate compressive stress, it will have no more strength to resist external force and will fail immediately. Concrete beam totally shows its elastic behavior and no cracks are occurred at this loading stage. [24]

2.6.2 Concrete Linear Elastic Cracked Phase:

When the applied external load is increased, the applied bending moment will also increase. When the tensile stresses in beam at the tension zone reaches the modulus of rupture of the concrete, internal micro-cracks start to develop throughout the concrete mass, mainly in midspan region of the beam. When external load is increased, concrete expands longitudinally exceeding the ultimate concrete tensile strain and cracks start to develop at the bottom of the beam. It is assumed that rubber is effective in resisting the force when concrete lost its tensile strength under loading. Rubber in concrete start to yield at this loading stage. As rubber is elastic material. With the increase in tensile stresses in beam, the beam starts to show larger deformation upon loading due to the elastic property of rubber. The entire section of the beam is still effective in resisting the bending due to the effect of added rubber. The rubberized concrete beam still shows linear behavior at this stage. [24]

2.6.3 Concrete Failure Phase

At this stage, the applied moment on the beam exceeds the cracking moment of the concrete. The maximum tensile stresses in the beam are also higher than the modulus of rupture of the concrete. The stress-strain distribution is no more nonlinear i.e. stress at any point within a beam member will no more depend upon the stress at corresponding level. Due to this, developed cracks start to extend towards the compression zone due to increasing loading. The neutral axis also shifts towards the compression zone. Diagonal shear cracks start to propagate towards supports. large deflection of the beam can be seen clearly due to the yielding of rubber at this stage. When the loads are increased, both concrete and rubber are no more effective in resisting tensile stress. Thus, they fail under tensile stresses before they fail in compression stress. At this loading stage, concrete also fails in compression stress when the strain of beam at compression zone reaches the maximum strain value of 0.003. The amount of rubber in concrete beam significantly influences the behavior of the beam in this nonlinear phase. [24]

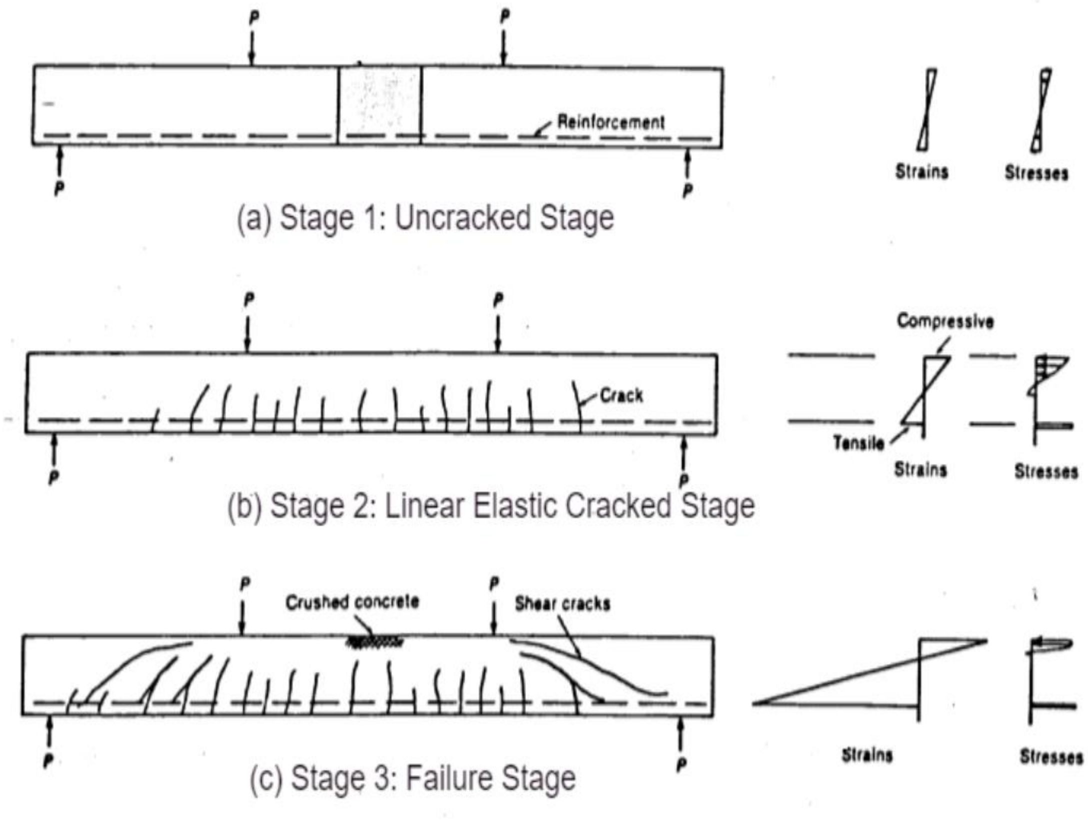

Figure 13:Flexural Behavior of a rubberized concrete beam under load

3 METHODOLOGY

3.1 Related Previous Studies

Many researches have been performed to study the effects of utilizing rubbers on the flexural properties of concrete. For better understanding the behaviour of rubberized concrete subjected to flexural loading, the results of previous related studies are analysed and discussed in this section.

3.1.1 Case Study I:

H.A. Toutanji performed experimental research to investigate the flexural properties of rubberized concrete. Twenty-five concrete beam specimens with five different concrete mixes were prepared for four-point bend testing experiment. Among those five mixes, one was just a normal concrete mix whereas the rest four were concrete mixes containing different proportions of rubber contents (25%,50%,75% and 100% by volume). No admixtures were added in concrete mix specimens. Shredded rubber tires with maximum size of 12.7mm were used as replaced aggregates. Specimens with total size of 100×100×350 mm were subjected to bending test after 28 days of curing period. [27]

Results and Discussion

Flexural strength of both plain and rubberized concrete specimens was determined from the bending test as shown in fig.14 (a). From fig.14 (a), it shows that flexural strength of concrete was gradually decreased when the percentage of rubber contents were increased. The flexural strength was reduced by 8%, 18%, 26% and 35% for concrete specimens with 25%,50%,75% and 100% replaced rubber aggregates respectively when compared to control specimen. The load deflection curve as shown in figure14 (b) shows the ductility behavior of concrete. As, ductility is represented by area under the load deflection curve. The curve shows that rubberized concrete exhibited higher ductility when compared to plain concrete. This is because of the effect of rubber that causes the concrete to undergo larger plastic deformation at ultimate load before the failure. Load-deflection graph also shows that the rubberized concretes exhibited higher energy absorption ability than plain concretes. [27]

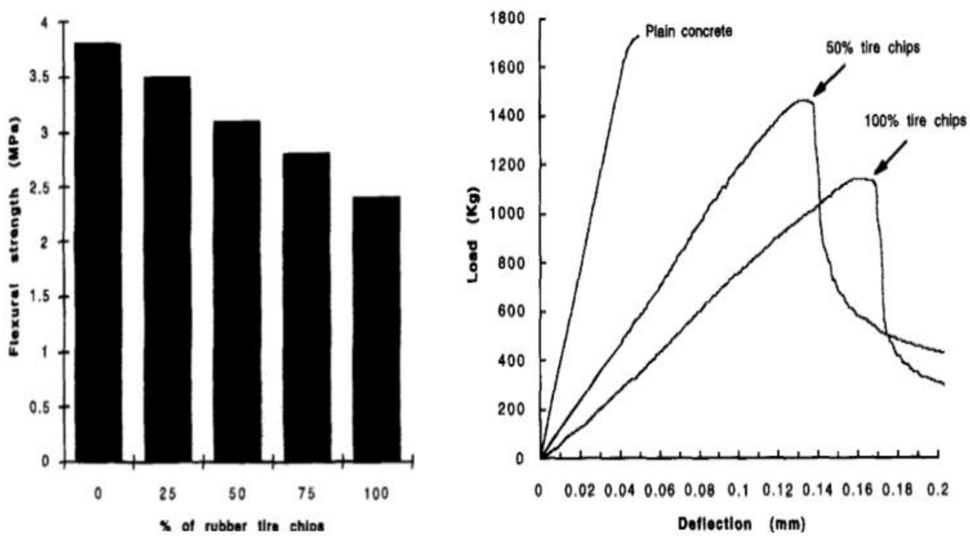

Figure 14:a)flexural strength of rubberized concrete and plain concrete beams (b) load-deflection curves for rubberized concrete and plain concrete beams [27]

3.1.2 Case Study II

Abu Babar et al. carried out experimental study to evaluate flexural behavior of rubberized concrete beam containing crumb rubber as fine aggregates replacement. Beam with a total length of 3000mm and depth of 200 mm was prepared for the test. Beam specimen with no replacement material (B1) and beam specimen with rubber materials (B2) were subjected to 4-point bending test for flexural analysis. [28]

Results and Discussion

From their flexural test results as shown in table 5, it demonstrates that the maximum applied loads at failure for plain and rubberized concrete were found to be 74.2 kN and 68.1 kN respectively. This shows that the flexural strength of concrete was reduced with the addition of replaced rubber. The mid-span displacement of rubberized concrete at failure was increased by 3% as shown in table 5. Increase in mid-span displacement at failure proves that the concrete beam loses its stiffness with the addition of rubber. From this result, it shows that rubberized concrete possessed higher deformability, ductility and higher energy absorption capability due to the effect of rubber. [28]

Table 5: Flexural Test Result [28]

Beam	Maximum Load (P_{max}) (kN)	Reduction of P_{max} (%)	Mid-span displacement (Δ_{max})(mm)	Increase of Δ_{max} (%)
B_1	74.2	-	30.4	-
B_1	68.1	8.3	31.4	3.2

Digital image correlation technique was used in the experiment to examine cracks development process in both plain and rubberized concrete. The technique was able to show the crack developments of both beams at first crack and failure as shown in fig.15 From their experiment, it was found that the cracks were developed earlier at the bottom of rubberized concrete at lower stress level when compared to plain concrete. Fig.15 shows that the number cracks are higher in rubberized concrete at failure. This is because of the poor adhesion between rubber and cement paste due to which tiny voids are produced higher in the concrete beam. Tiny voids are the reason for the crack development in concrete. Fig.15 also shows that the pattern of development of cracks is similar in both normal and rubberized concrete specimens. This indicates two things: (1) vertical cracks were produced in both loaded beams showing the flexural failure mode, and (2) the presence of rubber did not alter the packing characteristic of concrete. [28]

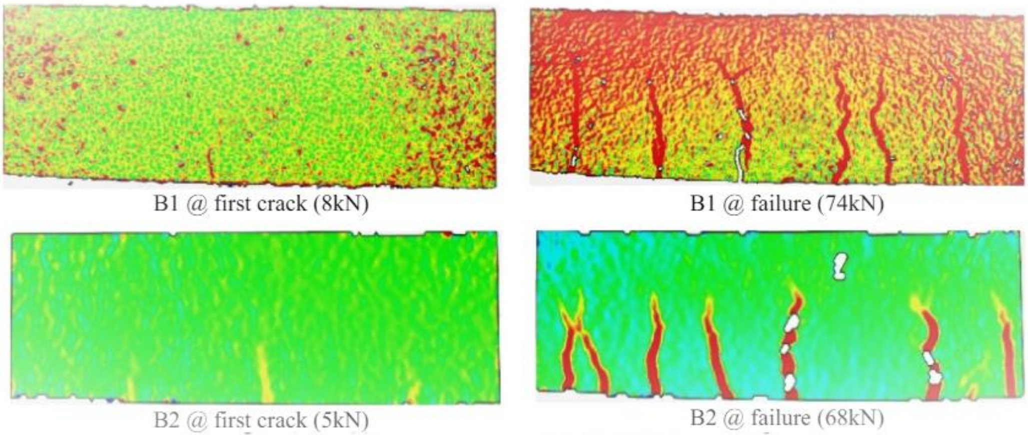

Figure 15:Development of cracks in both normal concrete beam (B1) and rubberized concrete Beam(B2) due to loading [28]

3.2 Finite Element Analysis of Concrete beams

Finite element method is applied for the flexural analysis of concrete beams. FEA analysis process involves of three separate stages: Preprocessing to prepare modelling data, Processing to assemble and solve equation, and Postprocessing to visualize analysis results. In this study, COMSOL Multiphysics software was used to execute the modeling and simulation of both plain and rubberized concretes with an aim to investigate their elastic behavior under a specific loading. Deflection, deformation, strain and stress values of loaded concrete beams were analyzed for this study. The finite element analysis of concrete beams was accomplished by performing following tasks.

3.2.1 Modeling of concrete beam

Three dimensional (3D) finite element model was constructed in COMSOL software for flexural analysis of concrete beam. Four different models of concrete beams were prepared. Among them, three were rubberized concrete beam containing 5%, 10% and 15% replaced rubbers respectively and the remaining one is the plain concrete as a reference model for the comparison. The geometry of each beam element is designed with a total size of 500 mm×100 mm×100 mm in accordance with ASTM C78 as shown in figure16. The dimensions of the beam were designed large enough so that a real structural element can be stimulated.

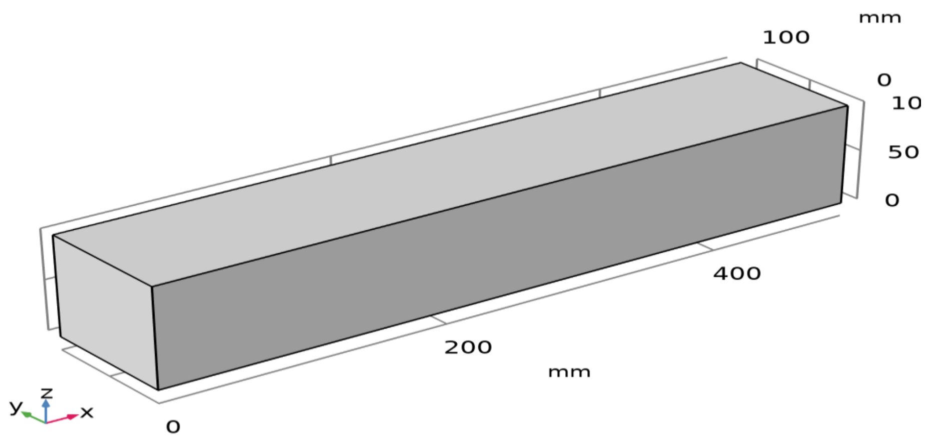

Figure 16:Geometric Model of Concrete beam

3.2.2 Reinforcement Model

Reinforcing rubbers are modelled as three-dimensional layered element. Geometric models of rubber layered element and concrete layered element were designed to create a 3-dimensional composite beam structure. Layer models were then attached together and modelled as a single layered elastic model as shown in fig.17, fig.18 and fig.19. Each structural layer was assumed to be isotropic, homogeneous and linearly elastic. The initial plan was to design concrete beam model with uniform distribution of rubber aggregates within the concrete matrix. Due to some limitations of COMSOL Multiphysics related to this type of design structure, 3D layered composite beam structure was created to study the effects of rubber in flexural properties of concrete beam subjected to loading.

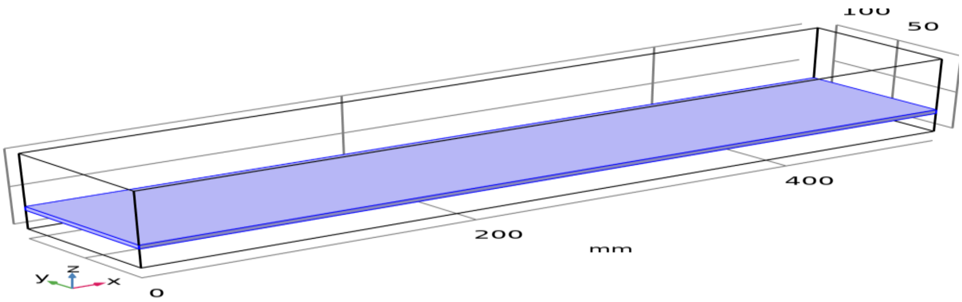

Figure 17:Reinforcement model of rubberized concrete containing 5% of replaced rubber

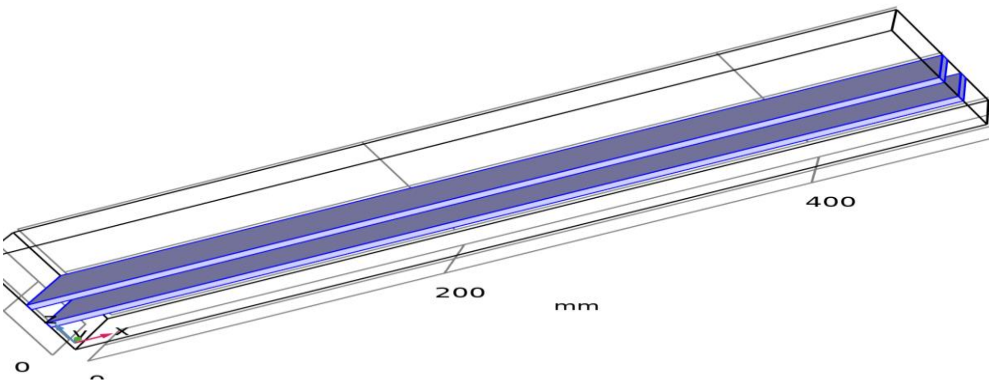

Figure 18:Reinforcement model of rubberized concrete containing 10% of replaced rubber

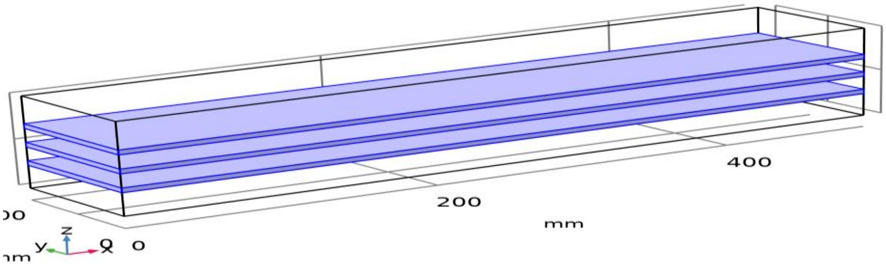

Figure 19::Reinforcement model of rubberized concrete containing 15% of replaced rubber

3.2.3 Material Properties

Two materials were required to be considered for modeling the rubberized concrete beam: Reinforcing rubbers and concrete beam. Those two parts were modeled with the applicable material properties available in COMSOL software. The material properties of concrete were available in the software, so it was easy to assign material properties to concrete part. But in case for rubber, material properties were determined from material property data provided in internet. The actual Poisson's ratio of rubber is 0.5. This Poisson's ratio value was not used to determine the properties of rubber in COMSOL Multiphysics. When the Poisson's ratio approaches 0.5, the mesh will not deform at all. So, the Poisson's ratio value 0f 0.49 was used for determining the properties of rubber. The essential input parameters to define the respective material properties of both rubber and concrete are displayed in table 6.

Table 6: Material Parameters

No	Name	Concrete	Rubber	Unit
1.	Density	2300[kg/m^3]	1522[kg/m^3]	kg/m^3
2.	Young's modulus	25e9[Pa]	0.1e9[Pa]	Pa
3.	Poisson's ratio	0.20	0.49	1

3.2.4 Loading, Boundary Condition and Meshing

The transverse mechanical load of 20kN was applied on the top of surface to produce bending moment in the structural element as shown in fig.20.The boundary condition was used to fix the both ends of the beam element so that the beam would not allow the vertical movement and the rotation. Then the meshing of the beam is done with the average element size of 20 mm. (see figure21)

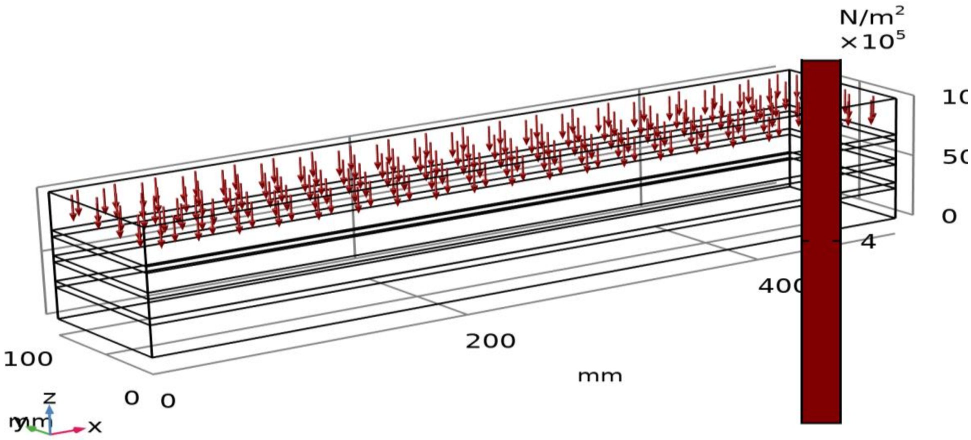

Figure 20:Distributed loading on concrete beam

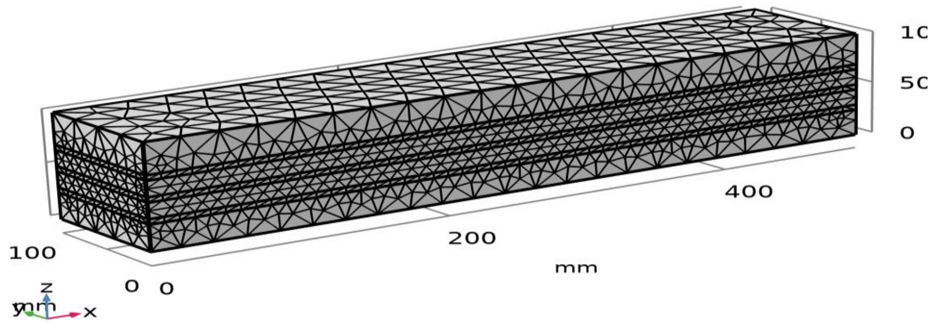

Figure 21:Mesh of concrete beam

3.3 Simulation Results

The simulation results were obtained from the finite element analysis of concrete beams by using COMSOL Multiphysics software. From the software, deflection, deformation, strain and stress values of plain and rubberized concrete beams were observed. The simulation results are listed in following sections.

3.3.1 Deformation of Concrete Beam

The results of maximum deformation of concrete beams obtained from FEM simulation are shown in fig.22, fig.23, fig.24, and fig25.

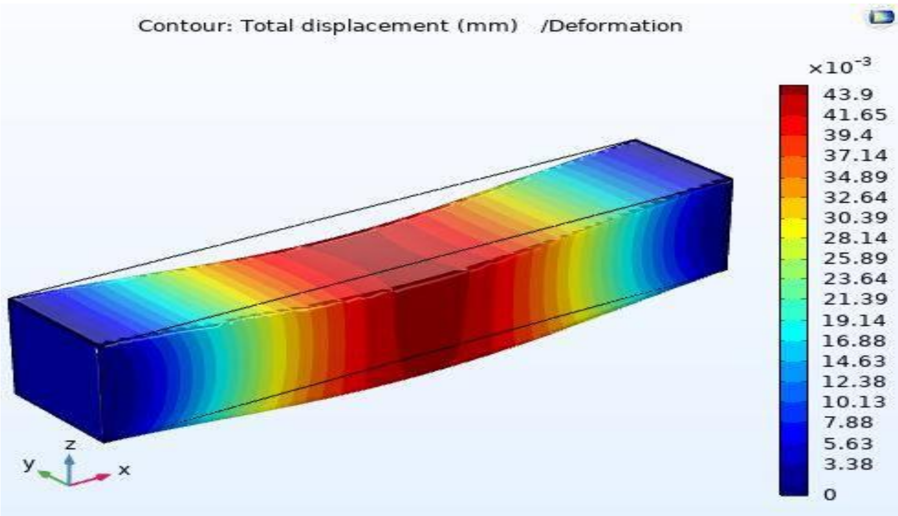

Figure 22:Deformed shape of plain concrete beam

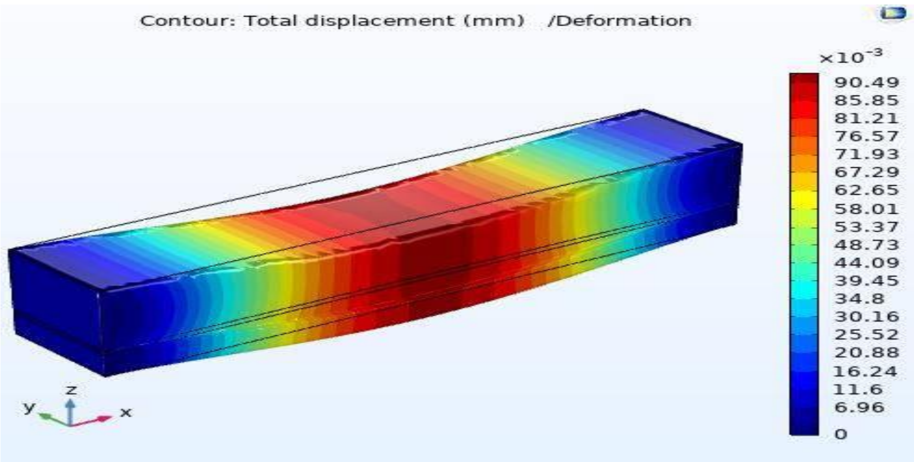

Figure 23:Deformed shape of concrete beam with 5% rubber

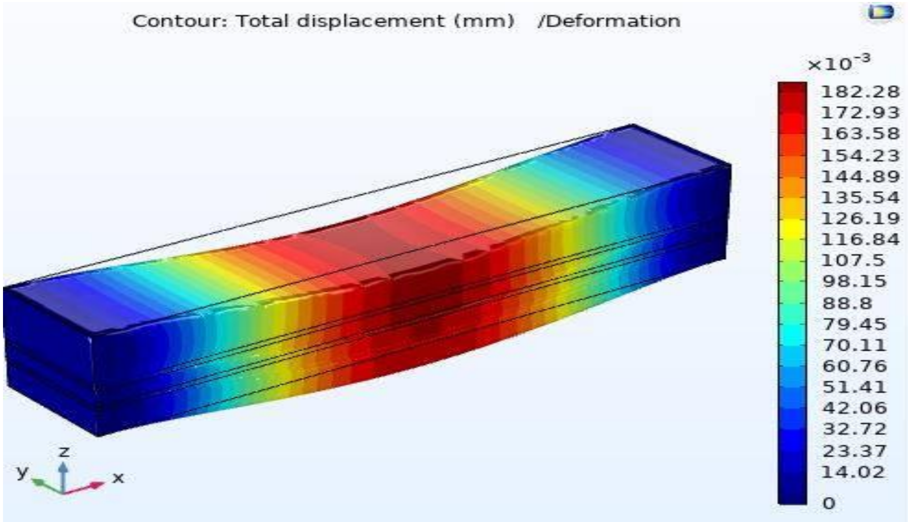

Figure 24:Deformed shape of concrete beam with 10% rubber

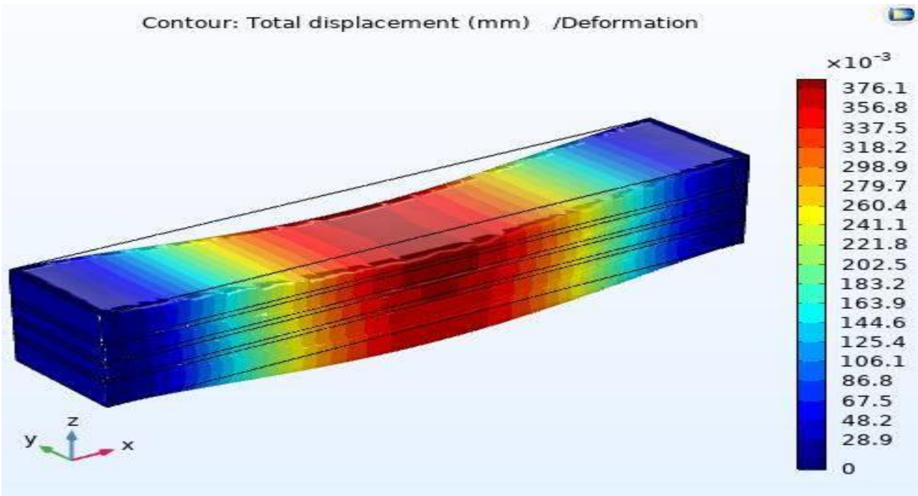

Figure 25:Deformed shape of concrete beam with 15% rubber

3.3.2 Average Surface Displacement of Concrete Beam

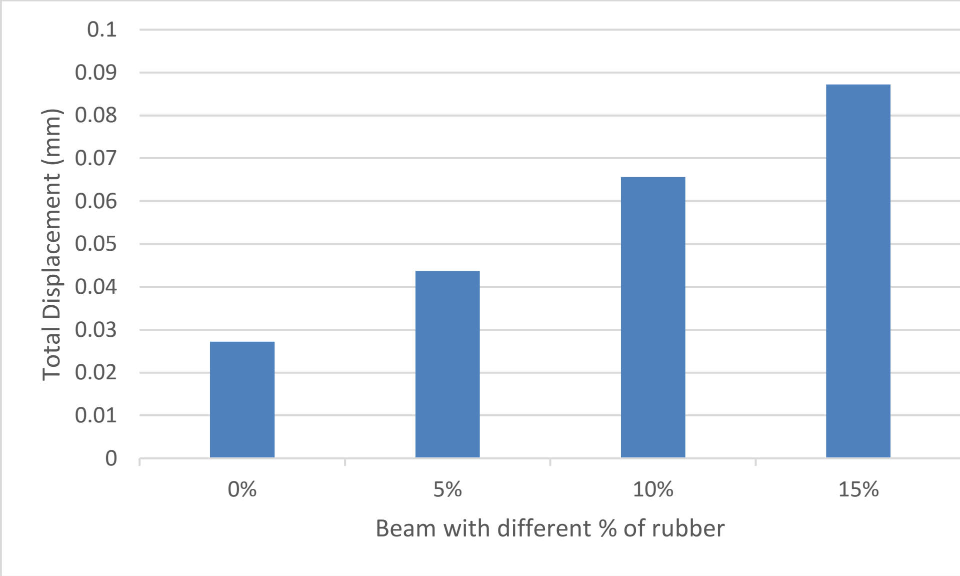

Figure 26:Average surface displacement of concrete beams containing 0%, 5%, 10% and 15% of rubber replacement

3.3.3 Total Deflection of Concrete Beam

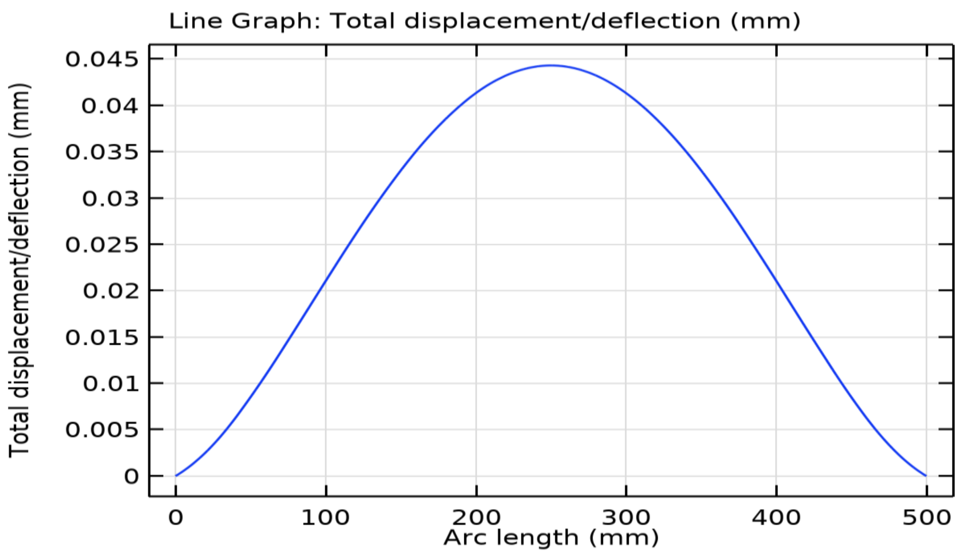

Figure 27:Deflection of plain concrete beam

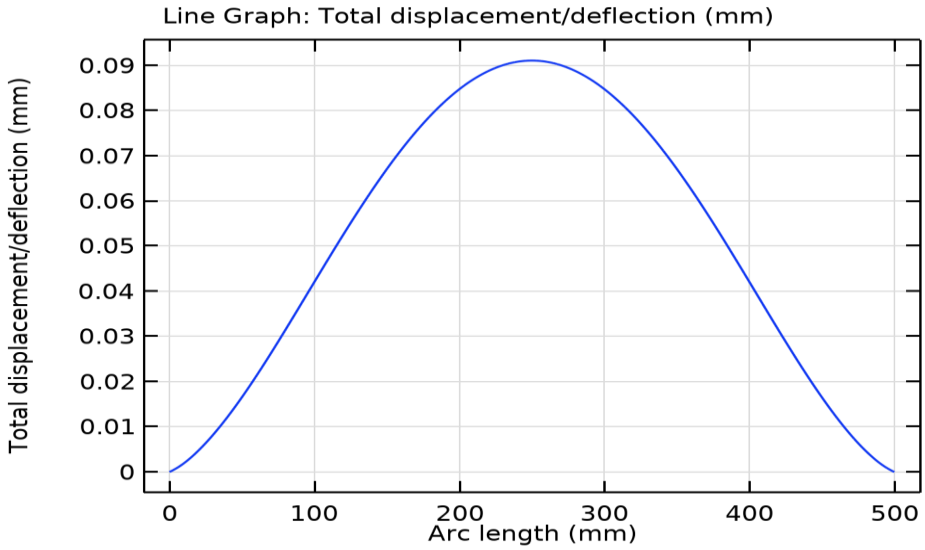

Figure 28:Deflection of concrete beam with 5% rubber

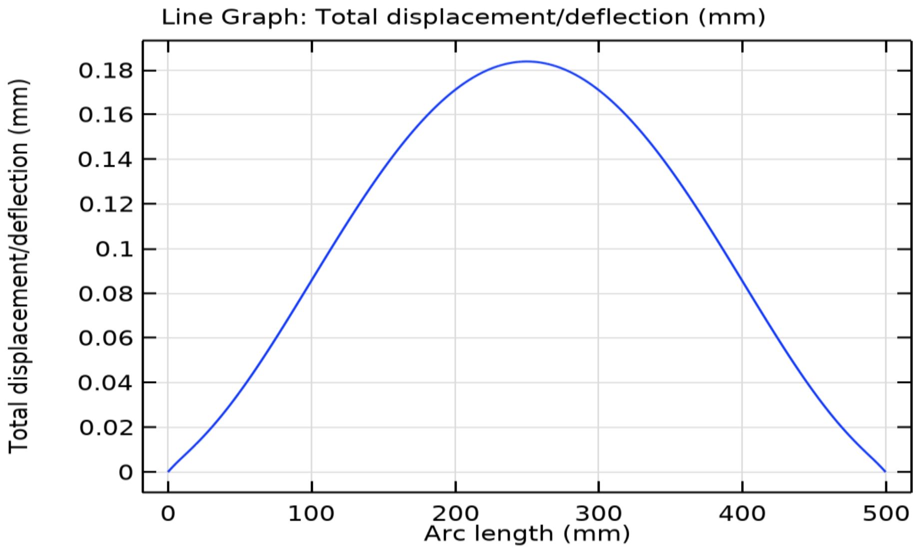

Figure 29:Deflection of concrete beam with 10% rubber

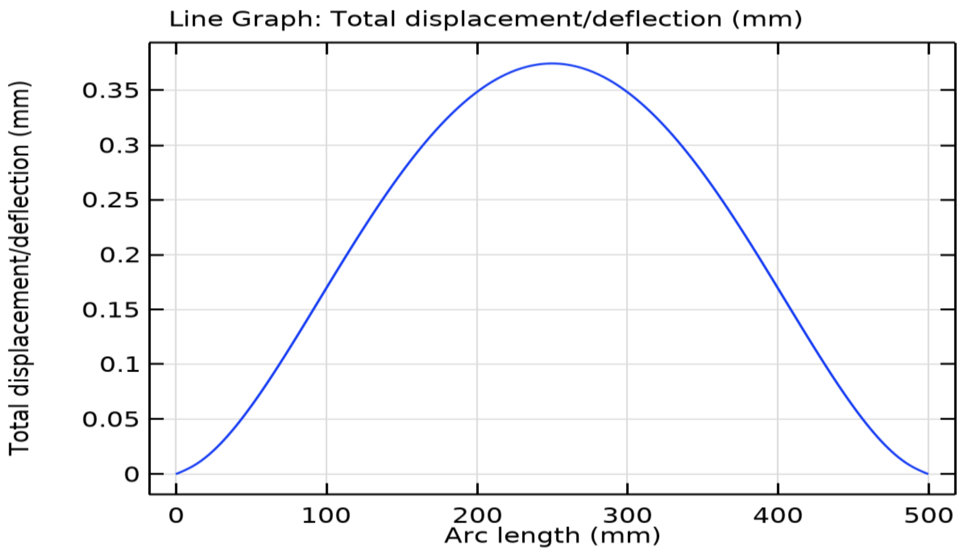

Figure 30:Deflection of concrete beam with 15% rubber

3.3.4 Bending Stresses in Concrete Beam

Fig.31, fig.32, fig.33, and fig.34 show the bending stresses produced in both plain and rubberized concrete beams due to bending.

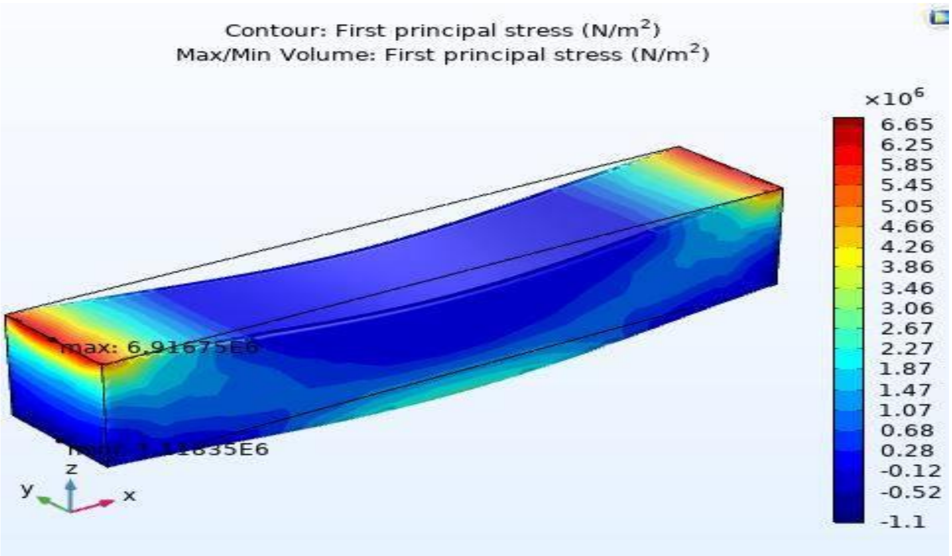

Figure 31:Stresses in plain concrete beam

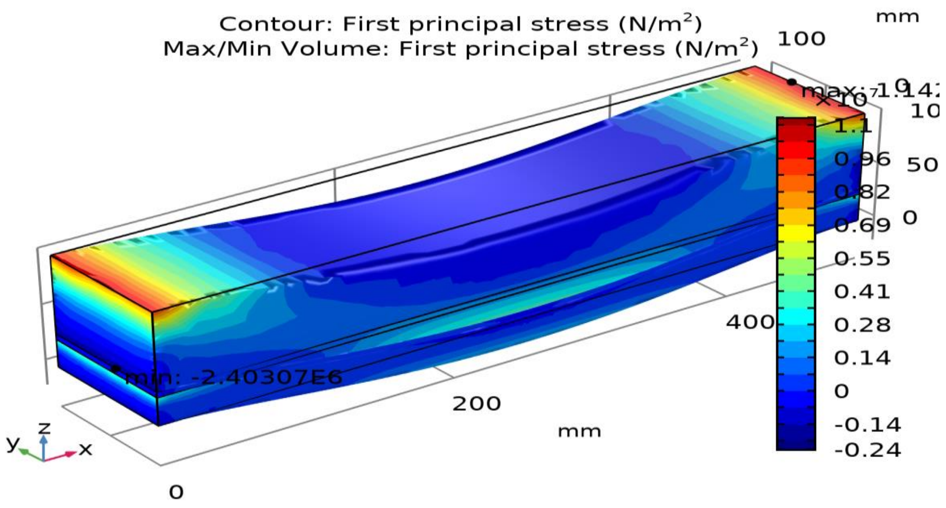

Figure 32:Stresses in concrete beam with 5% rubber

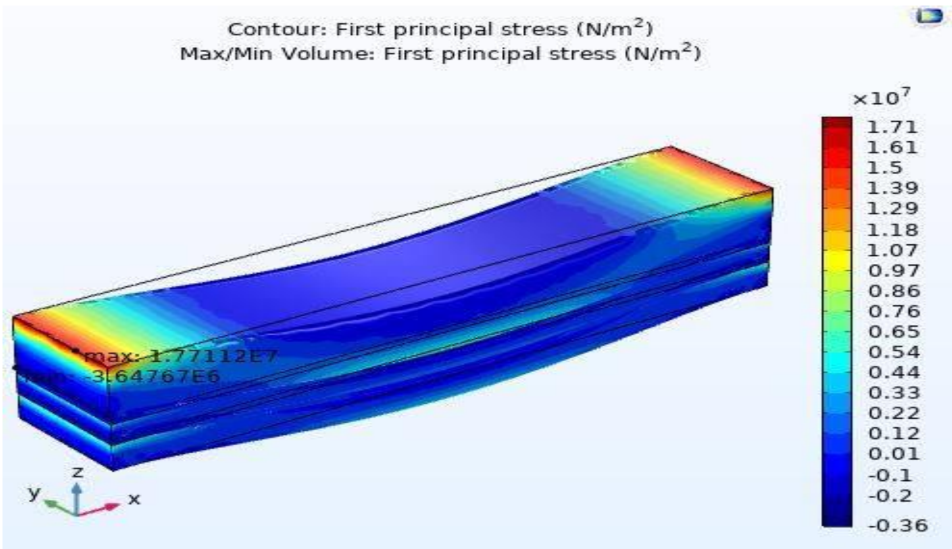

Figure 33:Stresses in concrete beam with 10% rubber

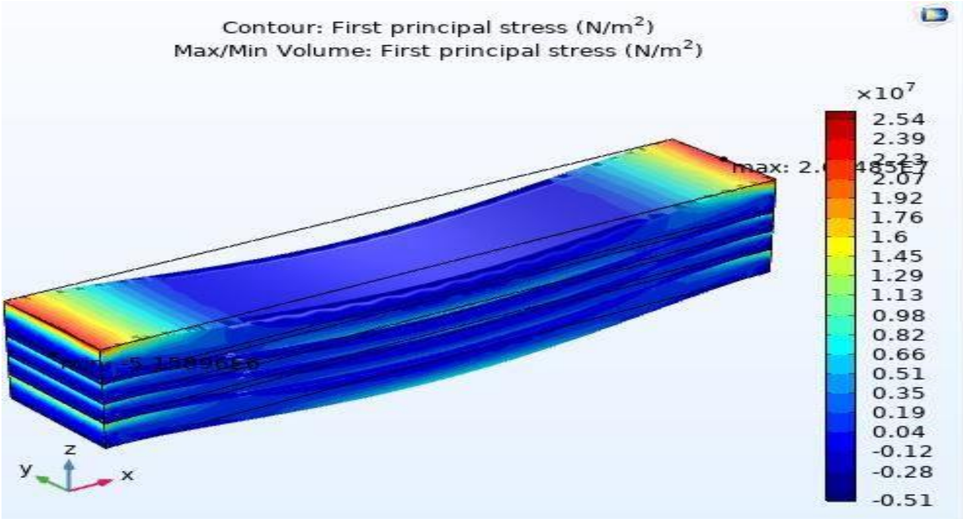

Figure 34:Stresses in concrete beam with 15% rubber

3.3.5 Comparison of Bending Stresses

Fig.35 shows the comparison of bending stresses produced in plain and rubberized concrete beams.

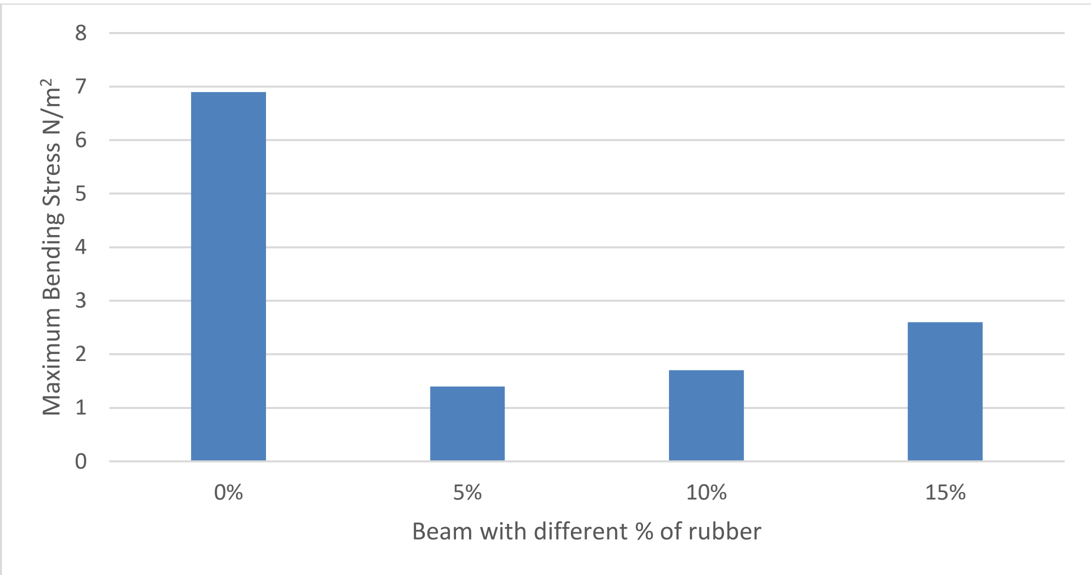

Figure 35: Maximum Bending stresses produced in plain and rubberized concrete beams

4 RESULTS AND DISCUSSIONS

The results obtained by using FEA are only approximations. These obtained simulation results only showed the linear physical behavior of concrete beams loaded in bending. Deflection, deformation, strain, and stress values of plain and rubberized concrete beams were obtained from the COMSOL Multiphysics as simulation results, which are discussed in this section.

4.1 Displacement and Deflection of Concrete beams

From simulation results of deformation of beams as presented in fig.23, fig.24, fig.25 and fig.26, it shows that the concrete beam showed higher deformation with the increase in replacement percentage of rubber. This is due to the low stiffness property of rubber particles incorporated in concrete beam. The average surface displacements of plain concrete and rubberized concrete beams with 5%, 10% and 15% replaced rubbers were found to be 0.0223, 0.05373, 0.10563 and 0.21608 mm, respectively. This indicates that incorporating rubbers can decrease the flexural stiffness of the concrete. It can be seen in deflection curve shown in fig.28, fig.29, fig.30 and fig.31 that the deflection of concrete increased with increase in rubber replacement percentage. This indicates the ability of the rubber to undergo large elastic deformation by absorbing the energy from the impact of the external load. Such deformation in concrete beam helps to reduce the maximum tensile stresses produced in a beam and hence enhances concrete tensile strength to avoid failure. Deflection curves also show that the concrete beams containing higher rubber replacement percentage exhibited excessive deflection during bending when compared to the plain concrete. Excessive deflection can be great problem for designing concrete structure. This is because excessive deflection causes excessive cracking and reduces the flexural strength of concrete.

4.2 Stresses of Concrete Beams

From fig.32, fig.33, fig.34 and fig.35, it shows that the maximum stresses were found at the supports of beam due to loading. Those stresses were produced due to the reaction of fixed supports to resist the bending moment caused by external load. The maximum principal stress produced in plain concrete beam was 6.9 N/m^2. The principal stresses of rubberized concrete beams with 5%,10% and 15% replacement rubbers were 1.14 N/m^2, 1.7 N/m^2 and 2.6 N/m^2respectively. The stress results of rubberized concrete beams shows that the maximum bending stress is produced higher in concrete beam containing higher percentage of rubber aggregates. However, the stress results show that excessive bending stresses were produced in plain concrete beam, which was not expected. That is may be because stresses in FEA results were analyzed through von Mises stresses, strains and displacement instead of analyzing the stress results in terms of tension, compression and shear stresses. Due to this, may be the unexpected value of beam was obtained. Or may be there could be some small errors in modelling, data input or in boundry conditioins which are hard to identify but play significant role in altering the result.

5 CONCLUSION

The basic idea of this thesis work is to determine the flexural behavior of rubberized concrete beam when subjected to loading in order to see how the flexural properties of concrete change with the replacement of natural aggregates by rubber particles. This thesis provided information about the general flexural behavior of rubberized concrete beam. Finite element analysis of rubberized concrete was performed by using COMSOL Multiphysics software. Further, some previous related studies on flexural behavior of rubberized concrete were studied and discussed to analyze the actual flexural performance of the rubberized concrete. From FEA results and previous studies, it was observed that the percentage of rubber aggregates can have significant effect on the flexural properties of concrete. Overall, it was found that incorporation of rubber can improve the flexural properties of concrete such as ductility, energy absorption capacity and deformability. From this study, it was found that some of the influencing factors like water/cement ratio, concrete mix, curing period, temperature, concrete compaction, and concrete shrinkage should be considered when designing rubberized concrete structure. These all factors can significantly affect the flexural properties of concrete.

Previous research studies concluded that the flexural strength of concrete was reduced with the incorporation of rubber aggregates. Reduction in flexural strength is mainly due to the week chemical bonding between the concrete and rubber particles. However, the results of the previous studies also showed that the flexural strength of concrete was only slightly reduced when the percentage of rubber replacement in concrete is low. In addition, it was also found that using rubber as replaced aggregates can enhance the flexural behavior of concrete as mentioned in the previous paragraph. Thus, it can be concluded that rubber can potentially be used as substitute for natural aggregates in concrete construction. The best rubber replacement percentage should be no more than 10% for the concrete mix to achieve effective flexural performance of concrete. Based upon these findings, we can say that rubberized concrete is not applicable for building concrete structures like bridges where high tensile strength concrete is needed. However, rubberized concrete can be used to construct non-load bearing concrete structures such as flooring, road construction, wall panels and so on. Thus, it also concluded that replacing natural aggregates with rubber can be the most effective way to solve the global waste tire problem. More studies should be carried to explore possibilities to enhance the flexural properties of rubberized concrete. In addition, I think similar types of studies should be carried out for hard-to-recycle rubber materials (like nitrile rubbers) in future.

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