KTH Architecture and
the Built Environment

EVALUATION OF ENVIRONMENTAL AND TECHNICAL PERFORMANCE OF ALTERNATE FIBRES FOR SHOTCRETE IN TUNNELS

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Master of Science Thesis
Stockholm, Sweden 2021

TRITA-ABE-MBT-2217

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Abstract

Tunnels in hard and jointed rock are normally excavated in an arch shape to enable the rock mass to support its weight. Since the beginning of the 1980's, fibre reinforced shotcrete (FRS) in combination with rock bolts have been the dominating support method for hard rock tunnels. This type of rock support is a complex composite structure in which the structural behaviour depends on interaction between shotcrete, rock and bolts. The design is commonly based on a rock mass classification system in combination with analytical solutions or finite element (FE) modelling. However, the in-situ variations of important properties of the shotcrete are normally neglected.

The aim of this thesis was to increase the understanding regarding the environmental impact of different fibre types used as reinforcement in shotcrete. First, a brief introduction to rock support and the role of shotcrete is presented. Along with this the technical performance and a short review regarding the production process involved in producing steel, synthetic and basalt fibres. To understand the environmental impact with respect to the production of different fibre types, environmental product declaration (EPD) from various producers were studied. Here, the environmental performance was studied from cradle to gate for the different fibres. The goal of this thesis was to study the global warming potential of fibres during the production stages and EPDs were used to compare the environmental performance for different fibres of different types and materials. For each fibre type different producers are also compared.

To study the environmental impact, a case study in which the shotcrete should fulfil a specified residual flexural strength, or a minimum energy absorption was used. Within this thesis, any potential effects of deterioration of fibres or the need of technical improvement during the technical lifespan was not included. Fibre dosages to fulfil the structural performance were selected based on the experimental testing from the literature. Finally, a detailed discussion regarding the optimum dosages of the different fibre types and their environmental impact is presented.

Keywords:

Shotcrete, Life cycle assessment, Environmental Product Declaration, Global warming potential, steel, basalt and synthetic fibres, flexural strength, energy absorption.

Sammanfattning

Tunnlar i hårt och sprucket berg schaktas normalt ut i valvform för att bergmassa ska kunna bära sin egenvikt. Sedan början av 1980-talet har fiberarmerad sprutbetong (FRS) i kombination med bergbultar varit den dominerande förstärkningsmetoden för tunnlar i hårt berg. Denna typ av bergförstärkning är en komplex sammansatt struktur där det strukturellt beteende beror på samverkan mellan sprutbetong, berg och bultar. Designen baseras vanligtvis på ett bergklassificeringssystem i kombination med analytiska lösningar eller finita elementmetoden (FE). Dock försummas vanligen in-situ variationer av viktiga egenskaper hos sprutbetongen.

Syftet med detta examensarbete var att öka förståelsen för vilken miljöpåverkan som olika fibertyper i sprutbetong bidrar till. Först presenteras en kort sammanfattning om bergförstärkningar samt sprutbetongens roll. Tillsammans med detta presenteras teknisk prestanda samt en kortare genomgång av tillverkningsprocessen för stålfiber, syntetfiber och basaltfiber. För att förstå klimatpåverkan som tillverkningen av olika fiber har samlades miljövarudeklarationer (EPD) in för att analysera miljöprestanda för dessa fibrer från råvara till färdigställd produkt (cradle-to-gate). Målet med denna uppsats var att studera fiberproduktionens bidrag till koldioxidutsläpp, här mätt med koldioxidekvivalenter (GWP). Produktbaserad EPD används för att jämföra miljöprestanda av olika fibrer. För varje fibermaterial jämfördes olika tillverkare.

För att studera klimatpåverkan av olika fibertyper används ett dimensioneringsexempel där sprutbetongen ska uppfylla en given residualhållfasthet eller energiabsorption. Inom ramen för denna uppsats studerades inte eventuella effekter av nedbrytning av fiber eller eventuella förstärkningar som behöver göras under tunnels livslängd. Lämpliga doseringar för de studerade fibertyperna valdes baserat på experimentella resultat från litteraturen. Slutligen presenteras en diskussion om lämpliga doseringar för de olika fibertyperna för att uppfylla de tekniska kraven med avseende på bärförmåga och en jämförelse av miljöpåverkan för dessa doseringar.

Detta examensarbete har bidragit till en ökad förståelse för miljöinverkan av fiber alternativ under deras produktionsskede.

Nyckelord:

Sprutbetong, Livscykelanalys, Miljövarudeklaration, Global klimatpåverkan, stål, basalt och syntetfibrer, böjhållfasthet, energiupptagning

Preface

This thesis work is carried out at the department of the Architecture and Built Environment, Division of Concrete structures at Kungliga Tekniska Högskolan, Stockholm, Sweden.

I would like to express my sincere gratitude to my supervisor Dr. Andreas Sven Sjolander for his constant support in technical knowledge and encouragement throughout my thesis. I would also like to extend my heartfelt gratitude to Larissa Stromberg, my supervisor from NCC for her guidance and support with my thesis.

I would also like to acknowledge Trafikverket, and different fibre manufactures for support.

Finally, a huge thank you to my family and friends for their belief and love throughout the journey of my master's studies.

Stockholm, December 2021

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Chapter 1

INTRODUCTION

Hard rock tunnels are excavated by the drill and blast method. These tunnels are stabilised by a complex interaction between the rock mass, rock bolts and the fibre reinforced shotcrete (FRS). The tunnel roof is normally designed with an arch shape to withstand and support the self-weight of rock mass. Rock bolts are used to support large and loose blocks while fibre reinforced shotcrete supports smaller block by a complex interaction between the rock mass, rock bolts and FRS (1).

Shotcrete, or sprayed concrete, is a type of concrete which is applied under pneumatic pressure against a surface. The velocity of the impact causes necessary compaction of the concrete (2). Shotcrete finds its major application in rock support, i.e., tunnelling, and slope stabilization. Fibres used in shotcrete play a major role in improving the crack resistance and ductility of the shotcrete. In Sweden, steel is the conventionally used fibre for shotcrete. This is due to the fact that a good theoretical and empirical knowledge of the behaviour of steel fibres under various conditions as reinforcement for shotcrete is available. All fibres are allowed in Sweden. However, in road and railway tunnels which are owned by Trafikverket, only steel fibres are allowed. But, due to its environmental impacts, the construction industries and researchers in this field are focusing on developing new alternate fibres as a sustainable option.

The European Union, including Sweden, is working on reducing the climate impact of products used within construction in order to meet the climate goals. Sweden is aiming to go climate neutral by the year 2045 (3). There is a great interest among Swedish public clients such as the Swedish Transport Administration (STA) and municipalities in using new and innovative solutions and choose materials used in the projects in order to make the infrastructure and construction industry more climate neutral (4).The market today offers various other fibre types like basalt and synthetic which could be a possible replacement for steel in FRS. In order to evaluate and assess environmental impact caused by production of alternate fibre types in comparison to that of steel, a comparative study based on environmental performance of the fibres are carried out. EPD acts as a very powerful document in assessing various impacts caused by products from their production stage, use-phase and recycling phase. This thesis will present the assessment of three types of fibres based on their technical performance and environmental performance to suggest alternative mix design for tunnelling shotcrete used for the project in Gothenburg (1).

1.1 OBJECTIVE

This thesis aims to evaluate steel, basalt and synthetic fibres from various producers by comparing their technical performance and climate impact and to suggest an optimal dosage for each fibre type. In this thesis we will be using EPD's to study and analyse environmental impacts of steel, basalt and synthetic fibres and to better understand the relationship between the type and dosage of fibres with respect to global warming potential. The fibres are analysed from its cradle to gate phase i.e., fibres will be assessed for environmental impacts at various stages of its production from raw material extraction, transportation, input energy flow, manufacturing process, products and co-products obtained to waste and emission output. Also, the technical performance of different fibres is compared based on a literature review. Review of various EPD's is conducted and out of the seven impact categories presented, fibres were evaluated based on the global warming potential. Moreover, a case study was carried out to calculate design mixes for each fibre type based on both empirical and analytical method of shotcrete design. Based on this, the best fibre alternative mix design ratio for FRS for the tunnelling project in Gothenburg was suggested.

1.2 LIMITATIONS

The thesis studied the environmental impact of different fibres used as reinforcement in shotcrete used as rock support in the Project Centralen. The thickness of the shotcrete was assumed to be constant and hence, the environmental impact of the shotcrete was not studied. This thesis concentrates only on comparison of the climate impact of fibres based on the EPD's from producers. The technical behaviour of fibres in shotcrete was addressed based on a literature review and no experiment regarding the same was carried out under this work. The study did not address the use phase, which refers to the maintenance and repair work during the lifetime of the tunnels. Also, the end phase of fibre which refers to recycling of fibres after its lifetime was excluded. This study assesses fibres only based on raw materials, energy input and output during manufacturing process of fibres and the transportation of raw materials to the manufacturing plant involved.

1.3 OVERVIEW

Chapter 2: Gives background knowledge of tunnel support systems, technical knowledge regarding shotcrete, design methods of shotcrete, fibres in shotcrete, production and structural behaviour of fibres and the causes for deterioration of fibres.

Chapter 3: Gives the methodology followed in this thesis, explaining EPD and LCA procedure in detail, literature reviews of LCA of fibres and the problem to be addressed in this thesis.

Chapter 4: Case study where the data collected regarding technical performance and environmental performance based on EPD's available from manufacturers of each fibre type is presented.

Chapter 5: Interpretation of the results for the climate impact and the technical performance for different fibres types compared. EPD for fibre types, technical comparison of fibre types and mix design for shotcrete with various fibres based on two design methods.

Chapter 6: Discussion of the results and conclusion of which fibre type would be better choice for shotcrete based on climate and technical performance of fibres and discussing future scope of research regarding the same.

Chapter 2

BACKGROUND

2.1 HARD ROCK TUNNEL SUPPORT MECHANISM

Tunnels excavated in hard rocks are designed around the principle that the rock mass is able to support its weight (5). Rock masses are in state of equilibrium with an initial state of stress before excavating a tunnel. Due to excavation, the blocks get disrupted around the perimeter of the tunnel and lose their support (6). Therefore, tunnels are excavated in arch shape and the stability of these tunnels greatly depends on interlocking between individual blocks (7). In hard rock tunnels, the support system consists of rock bolts and fibre-reinforced shotcrete. Rock bolts secure individual blocks by either spot bolting or systematic bolting. Grouting of rock bolts ensures in structural connection between rock bolts and rock mass while steel washer plates enable transferring of the load between shotcrete and the rock bolt (1). During the deformation of rock mass, the tensile force is created in bolts and compressing force is created between washer plate and shotcrete.

The compressive force from the washer plates gets distributed to create a compression zone at certain distance from the plate in the rock mass. Thus, a compressive zone is developed in the arch. Also there exist loose blocks between compressive zone, washer plates. The loose blocks existing in tensile zone are supported by shotcrete either by the bond strength between shotcrete and rock bolt or mechanical strength of shotcrete itself. Shotcrete fills up the rock joints to enable development of contact pressure between blocks and also seals the rock surface to prevent rock joints drying. The figure below illustrates the rock support system in tunnels (8)

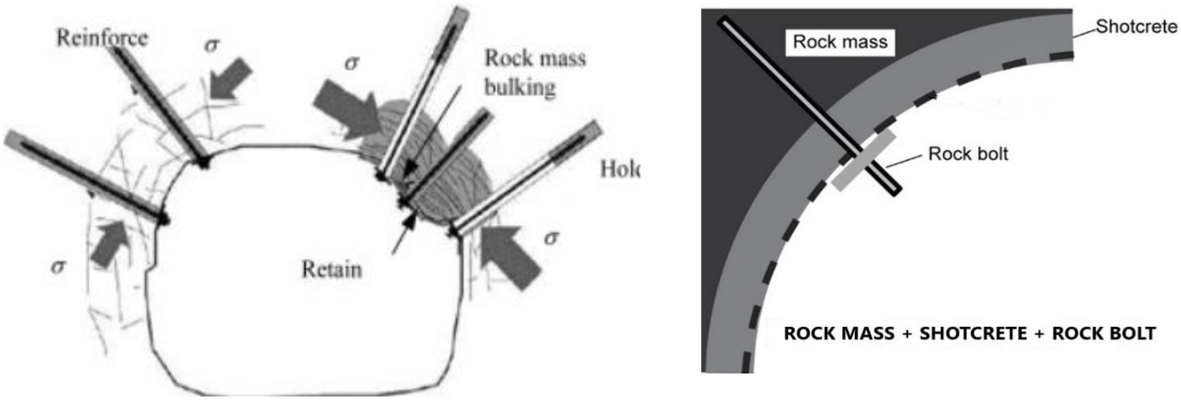

Figure2.1: Illustration of rock support system in tunnels.

2.2 DESIGN OF TUNNEL SUPPORT

Eurocode describes the rules to be followed and the conditions to be satisfied while designing any structures across Europe. According to the Eurocode 7, (9) which is used for design of all geotechnical structure, the limit state for structures should satisfy either, or a combination, of the following conditions:

1. adoption of prescriptive measures
2. experimental models and tests
3. the observational method
4. design calculations

The design of the rock support involves many uncertainties regarding inaccurate measurement of the rock mass quality, orientation of joints and water condition due to which the mechanical properties of rock are not obtained to high accuracy. Also, the loads acting on the rock support, structural deformation, and behaviour of the tunnel after excavation cannot be exactly predicted to precision. This is the reason why the above stated design approach is a suitable method to be adopted. Tunnels are support by a complex interaction between the rock mass, fibre reinforced shotcrete and the rock bolts. The loads acting on this complex system is difficult to be determined to precision and hence a classification system method is used to design the rock support system. This method helps in evaluating the rock quality by examining certain parameters to obtain a certain value which gives the rock quality value of the rock mass. Based on this value, along with the geometry of the tunnel, the rock support system is designed.

Shotcrete is designed based on different methods which are discussed in next section.

2.2.1 EMPHIRICAL METHOD

The rock support is designed based on rock mass classification in the empirical method. There are many classification systems of which these two methods listed below are most common methods used:

1. Q-method developed by Barton and others. (10)

2. Rock mass rating system (RMS system) developed by Bieniawski. (11)

1. Q-method:

The Q-method of rock mass classification was developed by (10) during the year 1947. According to this method, the amount and type of rock support is designed based on rock mass quality Q. This rock mass quality is a numerical value ranging between 0.001 and 1000, where 0.001 is the value for extremely poor rock quality with squeezing-ground and 1000 is the value for exceptionally good quality rock which is practically unjointed. The Q value for rock mass is a function of six different parameters with different ratios of importance. These parameters are the rock quality designation (RQD) index, the number of joint sets J_n, the roughness of the weakest joints J_r, the degree of alteration of filling along the weakest joints J_a, and parameters relating rock block size and inter block shear strength. These parameters are obtained by estimation from surface mapping and are updated constantly along with excavation. By this design method, a recommended support system is given by combinations of various shotcrete, bolting, spacing and length of bolts, thickness of shotcrete is provided.

The six parameters which describe and determine the value of Q are related by a formula given below:

$$Q = \frac{RQD}{J_n} * \frac{J_r}{J_a} * \frac{J_w}{SRF}$$

where,

SRF = stress reduction factor

RQD = rock quality designation

J_n = joint set number

J_r = joint roughness number

J_a = joint alteration number

J_w = joint water reduction factor

Further, on obtaining value of Q for the rock mass, rock support is designed based on the graph relating the Q value to the ratio of Span of height of the rock to excavation safety requirement as per the Modified Barton Chart given below (12)

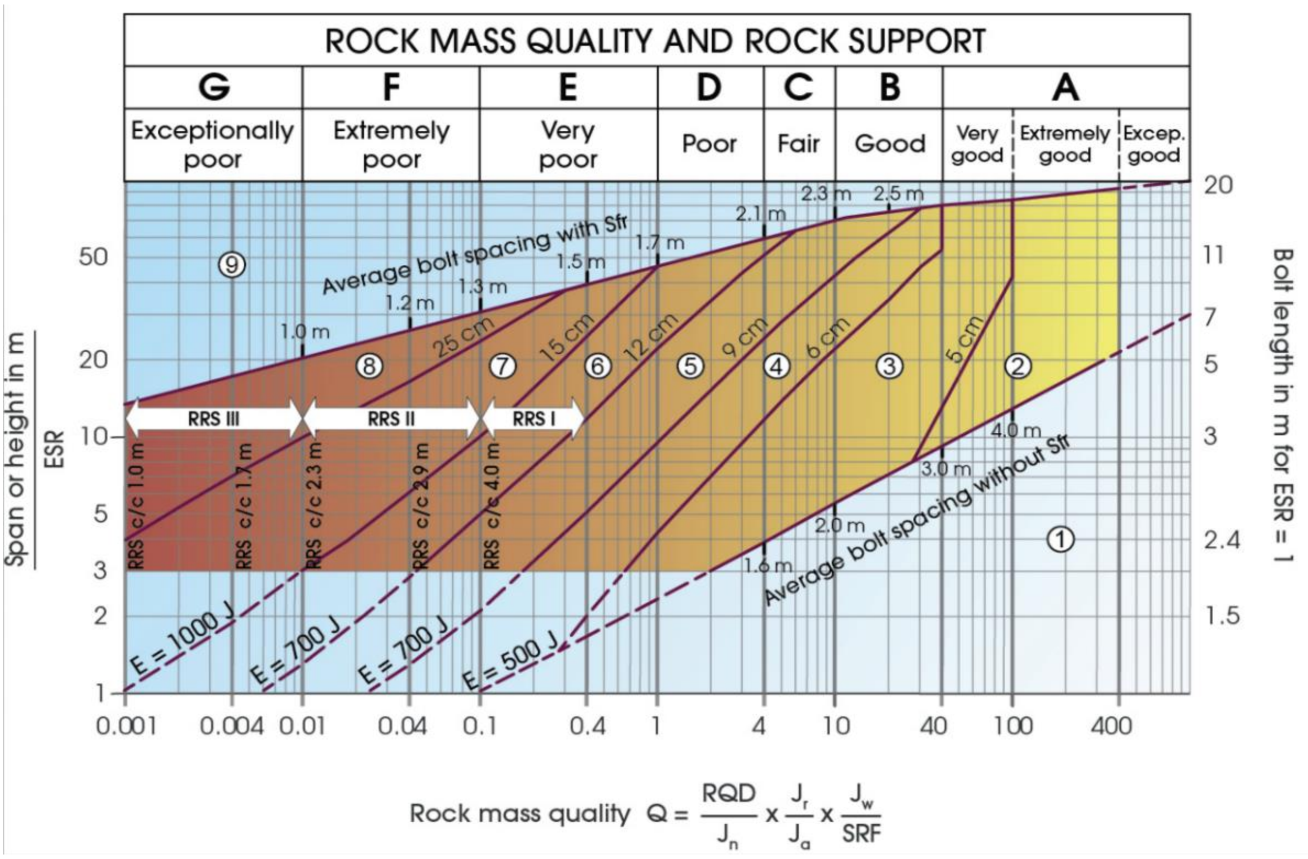

Figure 2.2: Modified Barton Chart (10).

2. Rock mass rating system (RMR):

RMR method of rock classification was developed by Z. T Bieniawski in the year 1972 (11). In this method, six of the most important geological parameters to obtain a comprehensive rock mass quality index is used to design the tunnel support. These six parameters are uniaxial compressive strength of rock material, rock quality designation, spacing of discontinuities, condition of discontinuities, groundwater conditions, orientation of discontinuities which are obtained from field surveys and laboratory tests (13). The RMR value is sum of these six parameters which ranges between 0 to 100 where 0 is for very poor rock quality and 100 is very good rock quality.

For tunnel design, stand up time, rock mass deformability modulus and rock mass strength are the charts which are used to estimate rock mass properties.

$$RMR = A1 + A2 + A3 + A4 + A5 + B \quad (14)$$

were,

A1 is rating for uniaxial compressive strength of the rock material

A2 = ratings for the RQD

A3 = ratings for the spacing of joints

A4 = ratings for the condition of joints

A5 = ratings for the ground water conditions and

B = ratings for the orientation of joints

The rock support can be estimated based on the RMR value from the special excavation and support table shown below.

Table 1: Relationship between RMR value and shotcrete thickness (15) .

Rock type	Rock quality	Shotcrete thickness (mm)	
		Roof / spring line	Wall
A	$70 \leq \text{RMR} \leq 100$	50	0
B1	$60 \leq \text{RMR} \leq 70$	50	0
B2	$50 \leq \text{RMR} \leq 60$	50	0
C	$30 \leq \text{RMR} \leq 50$	75	50
D	$0 \leq \text{RMR} \leq 30$	Special reinforcement, designed from case to case	

2.2.2 ANALYTICAL METHOD:

As described in (16) the convergence-confinement method (CCM) is the standard technique for preliminary analysis of the underground rock after excavation of the tunnel. This technique is used to estimate plastic zone extent, capacity of supports in the underground, radial displacement, and the final convergence of the opening (17). According to (18) the CCM, determines the tunnel behaviour and the required support pressure to control convergence. The ground reaction curve (GRC), the support reaction curve (SRC) and the longitudinal displacement curve (LPD) are used in this method. The relationship between the increasing radial displacement of the tunnel u_r and the decreasing internal support pressure p_i is given by the GRC curve. (19)gives the analytical relationship as:

$$u_r = \frac{R(1+\nu)}{E}\left[2(1-\nu)(\sigma_o - p_{cr})\left[\frac{R_p}{R}\right] - (1-2\nu)(\sigma_o - p_i)\right]$$

Were,

p_{cr} is critical support pressure defined as $p_{cr} = \frac{2\sigma_o - \sigma_{cm}}{1+k}$

σ_o is the in-situ stress defined as $\sigma_o = \rho g H$

k is the co-efficient of active earth pressure defined as $k = \frac{1 + sin\phi_{mass}}{1 - sin\phi_{mass}}$

R_p is the radius of the plastic zone defined as $R_p = R\left[\frac{2(\sigma_o\,(k-1)+\sigma_{cm})}{(1+k)(k-1)p_i + \sigma_{cm}}\right]^\wedge\frac{1}{k-1}$ and

σ_{cm} is the analytical rock mass compressive strength defined as $\sigma_{cm} = \frac{2c_{mass}\cos\phi_{mass}}{1 - sin\phi_{mass}}$

Similarly, (20) gave analytical relation of parameters represented by SRC between increasing support pressure p_s, increasing radial displacement of the support u_s. SRC is obtained by calculating maximum support pressure p_s^{max} and the elastic stiffness K_s of each support member. The mathematical equation of these parameters is given below:

for shotcrete equation:

$$p_s^{max} = \frac{\sigma_{CC}}{2}\left[1 - \frac{(R - t_c)^2}{R^2}\right] \text{ and } K_s = \frac{E_C}{(1 + \nu_c)R}\,\frac{R^2 - (R - t_c)^2}{(1 - 2\nu_c)R^2 + (R - t_c)^2}$$

while for rock bolt :

$$p_s^{max} = \frac{T_{bf}}{s_c s_i} \text{ and } \frac{1}{K_S} = s_c s_i\left[\frac{4l}{\pi d_b^2 E_s} + Q_b\right]$$

where

σ_{CC} is σ_C of the shotcrete

t_C is the shotcrete thickness

E_C is the Young`s modulus of the shotcrete

ν_c is the Poisson`s ratio of the shotcrete

T_{bf} is the ultimate load of the rock bolt

s_c and s_i are the circumferential and longitudinal bolt spacing

l is the rock bolt length

E_s is the Young`s modulus of the bolt

Q_b is the deformation-load constant

The LDP curve represents radial displacement along the longitudinal axis of unsupported tunnel.

Vlachopoulos and Diederichs (21) gave mathematical equation for the LPD of circular tunnel in elastic-plastic rock mass as per the equation below:

$$\frac{u_r}{u_{r,max}} = \frac{u_o}{u_{r,max}} exp(\frac{x}{R}) \;\; for \quad {}^{x}/_{R} \leq 0$$

$$\frac{u_r}{u_{r,max}} = 1 - \left[1 - \frac{u_o}{u_{r,max}}\right] exp({-3x}/_{R})/({}^{2R_p}/_{R}) \;\; for \;\; {}^{x}/_{R} \geq 0$$

were,

u_o is the radial displacement at the tunnel face and is defined

as $\frac{u_o}{u_{r,max}} = \frac{1}{3} exp(\frac{-0.15R_p}{R})$,

$u_{r,max}$ is the maximum radial displacement and

x is the distance from the tunnel face.

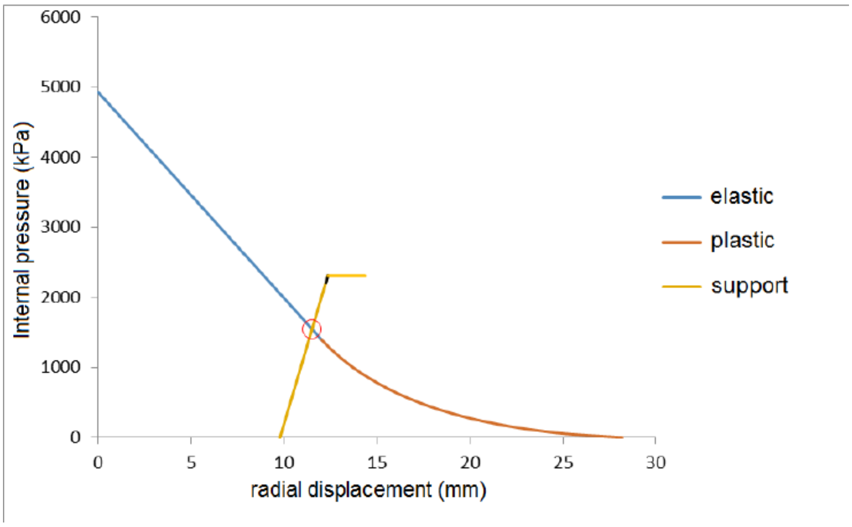

Figure 2.3: Ground reaction curve (22).

2.3 SHOTCRETE

The ACI Committee 1995 defines shotcrete to be pneumatically applied concrete at high speed. This spraying application of shotcrete makes it desirable to be used as for tunnel lining, slope and rock stabilisation, mining and also structural repair (23).

During 1900's Carl Akeley, while working on realistic animal models at Field Columbian Museum, happened to developed a machine to compress air to spray gypsum. This was later developed into "plaster gun" along with his colleague Clarence L Dewey to paint the old facades at the museum. This invention was named as "Cement gun " in 1910. In 1914, USA made its first attempt in using shotcrete while Europe and Iran are taws later in 1930 that shotcrete was used for the first time. During the initial years, dry - mix method was adopted to spay shotcrete until 1955. In dry-mix technique the cementitious mix consisting of cement, aggregates and the admixtures without water being added is used. A specialised machine designed to pressurise the cementitious mixture is used to pressurise the cementitious material and then added to high velocity air compressor. After this the mixture is sprayed by a nozzle with flexible hose. Clean water, additives or admixtures will be added at the nozzle to hydrate the material. The dry-mix shotcrete is used for concrete repairs, medium spraying concrete works, water proofing work. However, this method is less efficient and creates lot of dust when compared to wet- sprayed shotcrete. (1)

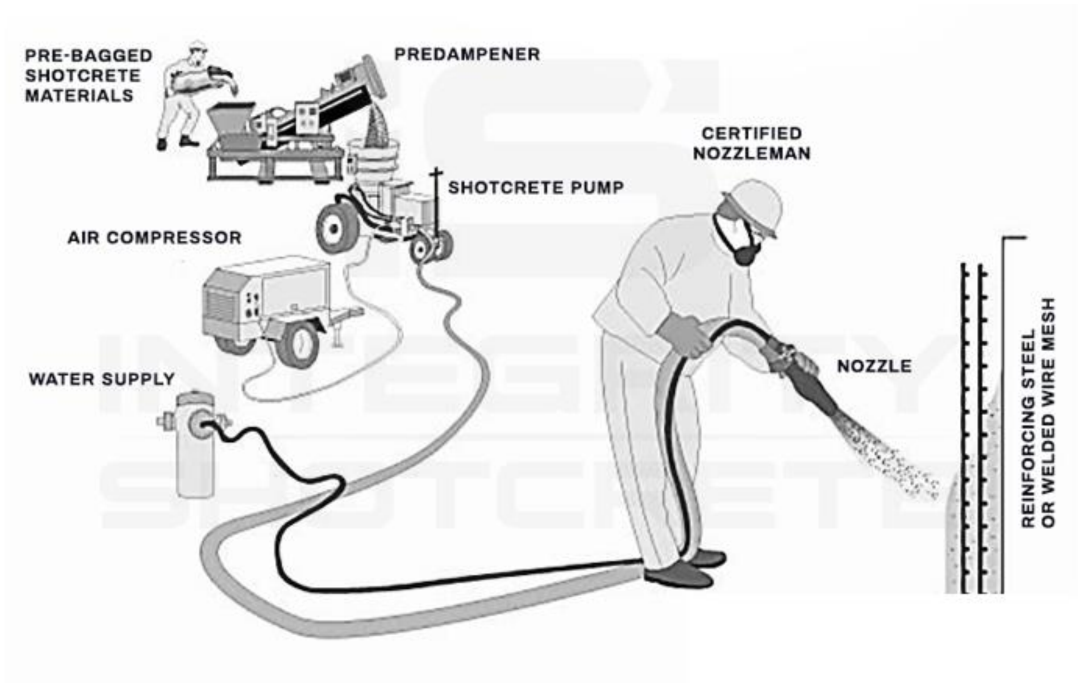

Figure 2.4: Shotcrete by dry-mix method (24).

During 1995, the wet-mix process was introduced. Wet-mix technique consists of regular ready-mix concrete with water added to the mixture of cementitious material and then it is fed to the concreting machine (1). The mixture fed to hopper of the shotcrete machine is pumped through a pipe to a discharging nozzle. At this nozzle high pressure air is introduced which creates sufficient impact to compact shotcrete by itself. Wet-mix shotcrete provides high output, high durability and better working condition which makes it widely used in present days. In 1970 fibres were introduced to shotcrete which was mixed at the factories, reducing time consumed on site to place steel reinforcement. Since 1980s, tunnels in hard rock are widely supported by the wet-mix fibre reinforced shotcrete method. Alkali-free set accelerators came in existence in early 2000s which played an important role in improving the strength development of shotcrete and making it feasible to spray thicker layers of shotcrete. Use of digital technology like LiDAR scanners to measure the thickness of shotcrete has been most recent advancement and is gaining more importance as it provides better control of spayed thickness. (25), (26).

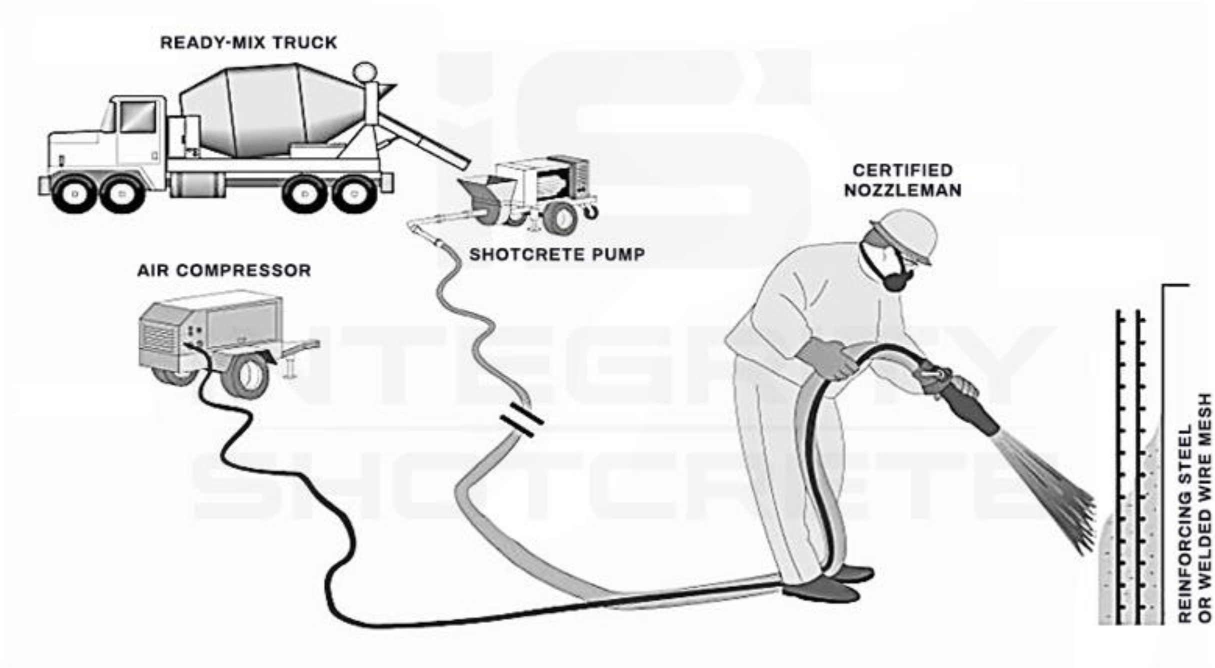

Figure2.5: Shotcrete by wet-mix method (24).

2.4 REINFORCEMENT FIBRES

2.4.1 STRUCTURAL BEHAVIOUR OF FIBRES

Fibre reinforced shotcrete is one of the most important material for tunnels and underground construction works. Fibres of different sizes are mixed with other materials and embedded in cement matrix to form fibre reinforced concrete (27). The volume of fibres to be added depends on the application and requirement (28). Fibres are added to improve the following properties of shotcrete like the:

- reduced the effect of cracking due to early - age shrinkage
- increased abrasion resistance

- improved ductility significantly
- small effect in improving flexural and shear strengths
- better fire resistance and protection against freeze-thaw attack

Fibres improve the ductility of shotcrete i.e., when a crack in the shotcrete lining develops due to high flexural stress, fibres provide excellent yielding support by taking in the tensile forces. The interaction between fibres and shotcrete increases the energy absorption of the tunnel lining. Fibres are added to internal matrix of other construction material like cement, sand and water and their main contribution is that they change the mode of failure from brittle to ductile. The dosage of fibre is expressed as percentage by volume or volume of fibres per volume of shotcrete (28).

Fibres are classified into two categories based on their size and function:

1. Macro fibres
2. Micro fibres

Macro fibres are structural fibres which improve ductility and fracture toughness. They are relatively larger, with length ranging between 25 to 60 mm and transverse diameter ranging within 0.3 to 3mm. Macro fibres find their application in instances like casting of concrete and shotcrete in which the volume of fibres is normally less than 1 percent. The reason for using a very small volume of macro fibres is that it would cause difficulties in mixing and spraying of concrete, also resulting in formation of fibre balling. Due to very small volume of fibre addition while using macro fibres, there is not a significant increase in strength but the major enhancement is observed in terms of toughness (28). On the other hand, micro fibres are very fine with transverse diameter less than 25 µm, and length less than 20mm.

Fibres have two modes of action after a crack develops in concrete. Strain-softening behaviour where first crack is developed by tension and this tension force cannot fully be absorbed by the fibres. This crack can become the only resulting crack if the fibre volume is too less or if the fibres are ineffective. This is because the fibres in cracked section cannot withstand complete tension force so there is reduce in load leading to no additional cracks. Due to this the single crack developed becomes wider resulting in large deflection (29). On the other hand, at strain-hardening behaviour, the fibres are sufficient to withstand full tension force once first crack develops and also withstand increasing load. This results in additional cracks in concrete and the first crack does not widen making structure more durable even when structure in exposed to corrosive environment (2).The mode of action for fibre-reinforced concrete after a crack depends on the type and dosage of fibre used (30).The graph below explains the stain-hardening and strain-softening behaviour of fibres by load-deflection curves.

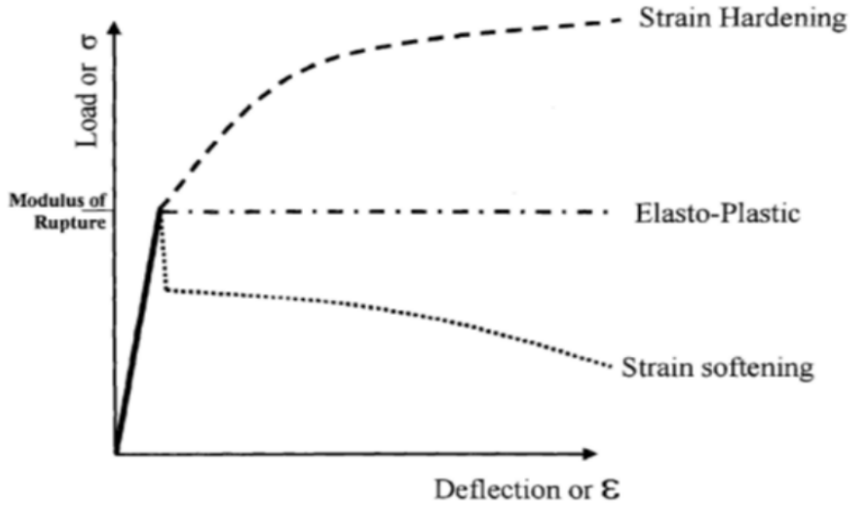

Figure 2.6: Load Vs Deflection Curve for Fibres (30).

2.4.2 STEEL FIBRES

Steel has been one of the most widely used fibre as reinforcement for concrete for many decades. Due to large use of steel, lot of research and empirical knowledge have been built up during the years which results in a good knowledge regarding mechanical properties and deterioration. Hence steel fibres find its application on wide rage within the construction industry. Also, steel is available in various sizes and shapes making it the most dominating fibre reinforcement.

PRODUCTION OF STEEL FIBRES:

Iron ore, a compound of iron, oxygen and other minerals from nature like carbon, small amount of manganese form the main constituent of steel. The raw materials for manufacturing of steel are obtained by mining and production of steel involves two processes i.e., the blast furnace/basic oxygen furnace, and the electric arc furnace (31). A blast furnace uses air which is forced into the furnace from the bottom into the heated stoved area. Electric arc furnace uses two different types of electric currents to create the heat. While liquid iron is used in blast furnace to make steel, electric arc furnace used scrap steel to make steel. (32)

Coal and iron ore are the two major raw materials involved in steel production. Along with coal and iron, scrap steel also becomes raw material in steel manufacturing. These raw materials are melted into liquid form by blast furnace or by direct reduced iron process. Steel obtained is cast using casting machines and then transformed into different shaped by either hot or cold rolling. Once the steel is rolled out in various shapes and sizes, it is followed by process like annealing, galvanising and organic coating to produced finished products. Alloying the iron with other metals like chromium, molybdenum, aluminium, titanium, cobalt etc. gives steel different useful properties. (33)

Steel fibres have a very high modulus of elasticity which is around 200GPa and the tensile strength can be as high as 2500MPa (34).

APPLICATION OF STEEL FIBRE REINFORCED CONCRETE:

Due to its high demand, producers are constantly manufacturing modified steel fibres to satisfy various demands and conditions. The most common application of steel fibre is found in concrete for pavements, tunnel linings, slabs, shotcrete, bridge deck, innings of irrigation channels. Also, steel fibres are suggested to be used as reinforcement for earthquake zones due to its high energy absorption capacity (28). The most beneficial use of steel fibres is most often in cases where it is difficult to place ordinary reinforcement.

ADVANTAGE AND DISADVANTAGES OF STEEL FIBRES

As discussed in the thesis by (28), addition of steel fibres significantly helps in improvement of ductility and failure toughness in shotcrete. Also, there might be a slight influence in improving flexural strength, tensile strength, impact strength and shock resistance. Steel reinforcement increase surface resistance to abrasion and erosion. It minimizes appearance of cracks by improving ductility in concrete.

While using steel fibres the main concern is that when exposed to humid environment, steel undergoes corrosion leading to a reduced ductility and post-cracking structural performance. In the worst case, this could lead to failure of the structure in the long run. When fibres are added to concrete, improper mixing can result in balling of fibres. Addition of too much fibres has a negative effect on the rheology of the concrete, i.e., one cannot add too much fibres since this impacts the ability to spray concrete. Also, production of steel has now drawn environmental attention as there is a greater need to adapt environmentally friendly methods of production.

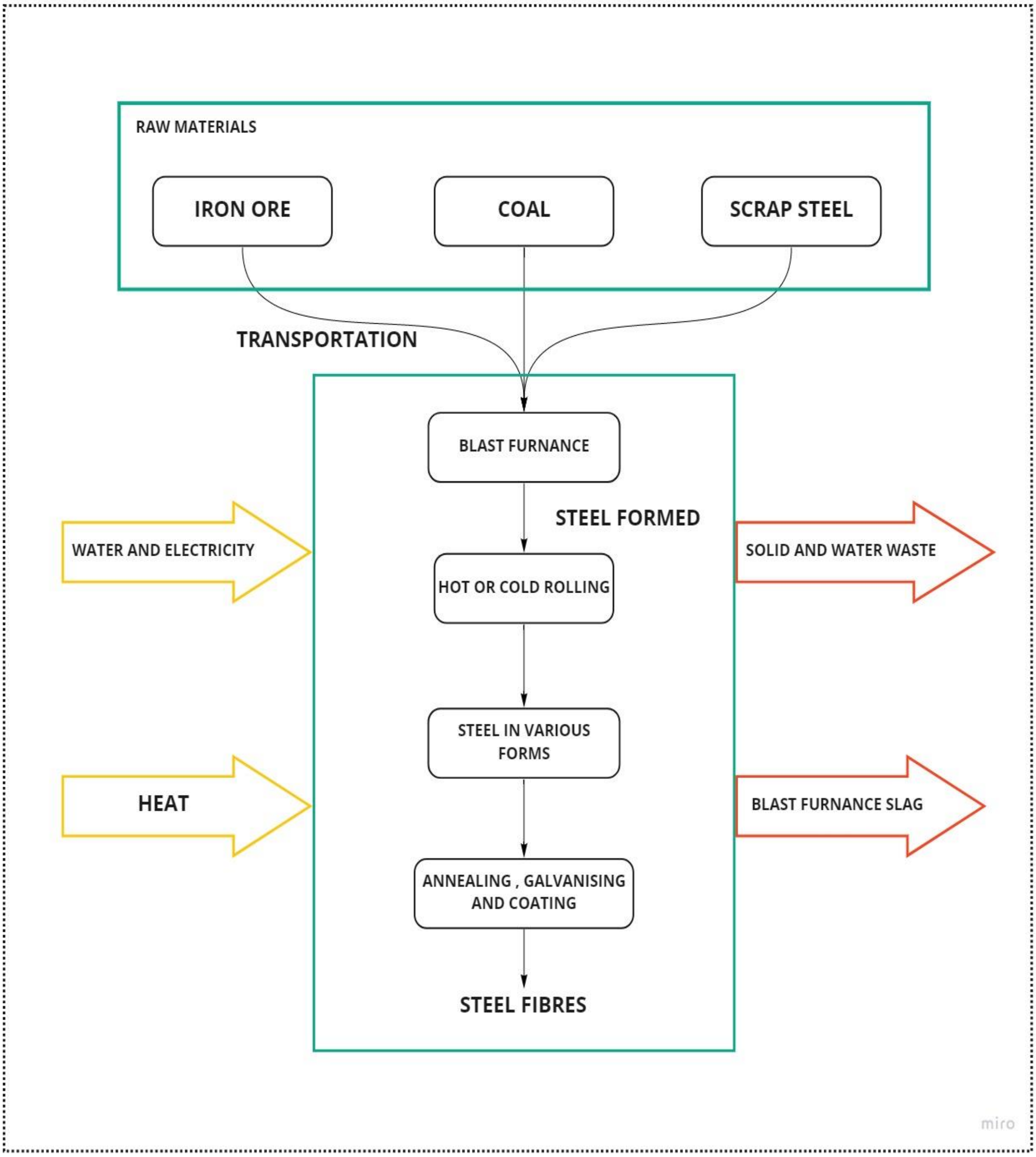

Figure 2.7: Schematic representation of production of steel fibre.

2.4.3 BASALT FIBRES

Basalt fibres are obtained by crushed basalt rocks melted at a temperature as high as 1400-degree Celsius. They are high-performance inorganic fibres introduced by an American scientist in the year 1923. Initially basalt fibres found its application in protective structures during the World War 2. Later years, due to research and develop, it is used in various fields like aeronautics, military, infrastructure (35).

Jamshaid and Mishra described basalt fibres as green industrial material and addressed it as "twenty-first century non-polluting green material" as manufacturing process of basalt fibre does not include any chemical additives which makes it more environmentally friendly (36).

PRODUCTION OF BASALT FIBRES

Basalt fibres are produced by one-stage process which involves melting and extraction of basalt fibres from crushed basalt. Basalt rocks are naturally found in quarry sources which is crushed and washed. The raw material of basalt is then converted into fractures of 5 mm to 20 mm size which is melted by heating in a melting furnace to a temperature between 1400-1600 degree Celsius. The molten rock then flows through die holes of the bushing and the fibres are extruded through nozzles with a diameter of 9 mm to 15 mm. These fibres are then coated in lubricant unit and winded into spools to produce continuous fibre of basalt. These spools are rewound later into bundles (37)

The process of basalt fibre production is shown in the flow chart below in the figure 2.8

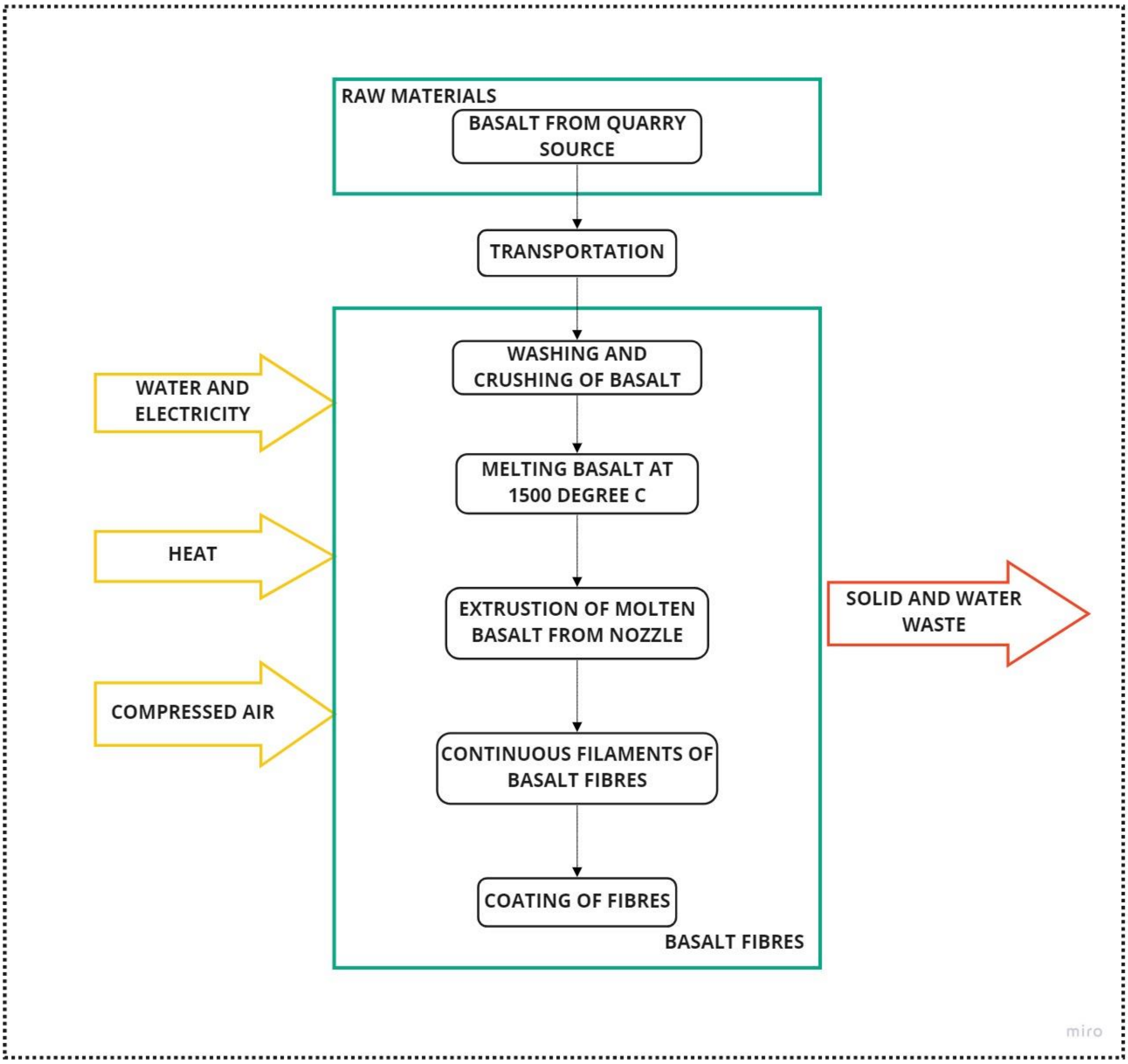

Figure 2.8: Schematic representation of production of basalt fibre.

APPLICATION OF BASALT FIBRES

Basalt fibre find application in different fields like aeronautical, military and infrastructure. Due to its increased application and advantages, there is continuous research encouraged in all the fields to gain more knowledge about the properties of these fibres at various parts of the world (35).

ADVANTAGES AND DISADVANTAGES OF BASALT FIBRES:

Basalt fibres exhibit main advantage in fire resistance, resistance against chemical environment, insulation against vibrations and noise (38). Basalt fibres are proven to be strong corrosion resistant, non-carcinogenic and non-toxic products as discussed by (28). (35) mentioned that using of basalt fibre has an advantage in enhancing energy absorption capacity which helps to reduce damage in a structure due to energy dissipation. Thus, improving material energy storage capacity in concrete.

Although basalt exhibits high tensile strength in the elastic range, the profound ductility of the material leads to brittle failure. However, the main failure mechanism of fibres is sliding. Due to this, tensile failure of the fibres is very rare and the low ductility of fibres is not necessarily a disadvantage. Furthermore, there is no proper knowledge existing regarding the optimum dosage of fibre or the volume fraction of fibre for a basalt reinforced concrete mix which poses necessity for further studies to be carried out to explore the application of basalt fibres (39).

2.4.4 SYNTHETIC FIBRES

Synthetic fibres used in concrete are made of manmade material. They are synthesized polymers of small molecules obtained from petroleum-based chemicals as raw materials. There are various kinds of synthetic fibres available in market that are used in concrete as reinforcement like acrylic, aramid, caron, nylon, polyester, polyethylene and polypropylene. The synthetic fibres are categorised as micro and macro synthetic fibres. Micro fibres which are polypropylene based are used to control plastic shrinkage in concrete and to improve fire resistance behaviour of concrete at a very high temperature. Macro synthetic fibres based on polypropylene help in improve crack behaviour of concrete.

PRODUCTION OF SYNTHETIC FIBRES:

Synthetic fibres are produced by combination of raw materials in different proportions based on requirement as per manufacturers. Virgin polypropylene, recycled polypropylene, polypropylene recovered from old waste is combined together along with additives heated at high temperature to form fibres. These fibres are extruded and finished by cutting to different lengths.

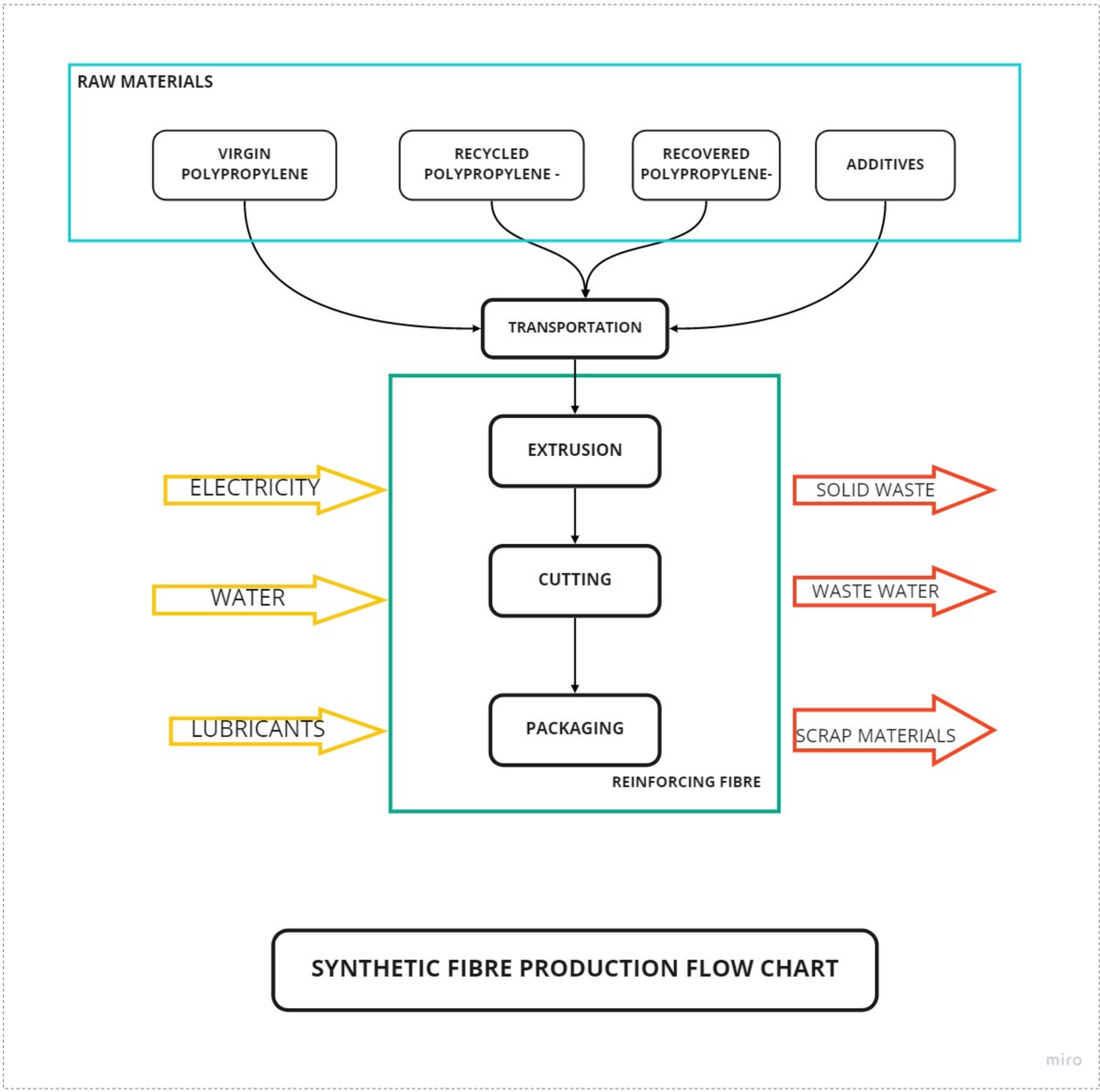

Figure 2.9: Schematic Representation of Production of Synthetic Fibre.

APPLICATION OF SYNTHETIC FIBRES:

Synthetic fibres made their appearance over few decades ago in the market as a possible replacement to steel fibre. Synthetic fibres find application in rock support for stabilizing tunnels, slopes and underground mines. However, due to a combination of lack in practical experience and theoretical knowledge regarding long-term structural behaviour, the use of synthetic fibres is still limited and requires more research to be carried out in this regard.

ADVANTAGES AND DISADVANTAGES OF SYNTHETIC FIBRES:

Synthetic fibres have lower modulus of elasticity in comparison to steel which is around 5-15 GP. However, due to the low E-modulus, these fibres are more efficient at larger deformations. Synthetic fibres also play significant role in improving the ductility of the shotcrete

Like other fibres, addition of synthetic fibres also helps to reduce plastic settlement cracks, reduces plastic shrinkage cracks. It increases impact and abrasion resistance (40). Unlike steel fibres, synthetic fibres are corrosion resistant (27). Synthetic fibres are mostly used for light loaded structures and not in heavily loaded structures as they tend to creep. Hence when structure is designed in crack state under long term loading, the fibres do not save the structure from failure.

Chapter 3

METHODOLOGY

3.1 LIFE CYCLE ASSESSMENT:

Life cycle assessment (LCA) is a standardized process to compile and evaluate all the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (41).

This includes everything from procurement of raw materials or generation from natural resources to the final disposal. LCA is carried out according to a series of standards by the international organisation for LCA which are of 1SO 14044 and ISO 14040 (41) (42).

LCA can be organised into four different phases by the standards which are as follows:

1. Goal and scope definition
2. Inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation

According to the ISO standards there are two type of studies which are life cycle assessment studies and life cycle inventory studies (LCI). LCA includes LCI as a phase while LCI studies is similar to LCA but does not include the assessment phase of life cycle inventory.

The interaction between different phases of LCA is schematically represented in the figure.

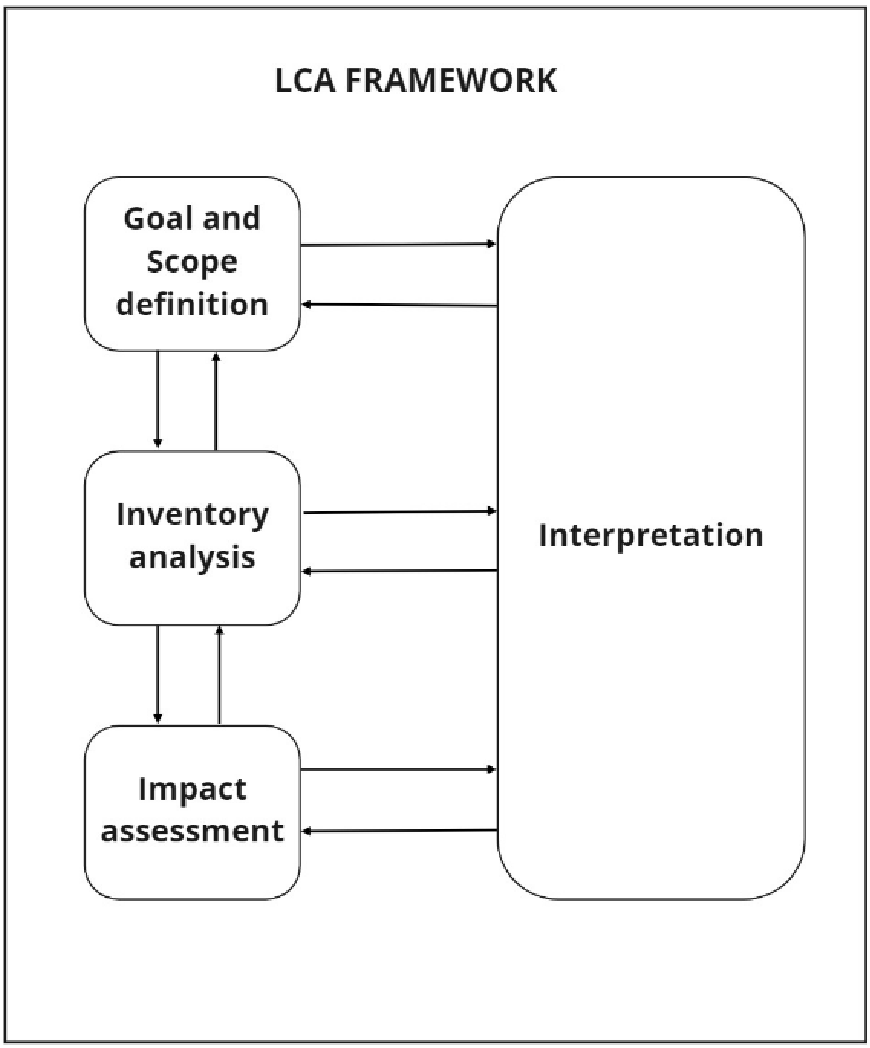

Figure 3.1: Frame work of LCA (43).

The scope of a LCA includes system boundaries and level of detail, while the goal defines the depth and breadth of the LCA. While conducting an LCA, the boundary conditions define what has been included and excluded. For example, in this thesis, the study is regarding LCA of fibres in which the system boundaries are set only to the production phase of the fibres. The use phase and recycling phases are not included. All the energy, processes and transportation used in the production phase and the emissions during this phase are only considered for the study. Similarly, the goal defines the aim of the study, e.g., the purpose and the main focus of the study. The goal of the study presented here is to analyse the environmental impact of the fibres caused by the production phase of fibres.

Inventory analysis is the second phase which deals with data collection regarding all the input and output inventory data involved in the system. In general, inventory data includes all the raw materials, processes and energy source used as input during the life cycle of the product. Also, the transportation facilities used to include the mode of transport and the distance travelled during this phase is considered. All types of emissions such as: emission into air, water, soil and the by-products or the solid waste and their transportation are considered as the output inventory. Further recycling of these wastes or treatment of these wastes are considered depending on the scope defined. Data collection could be the most challenging part of LCI as there would be lot of uncertainties involved in the data collected, also there is lack of proper data available. In this thesis, initially production flow chart for all the fibres were created to understand different processes and raw material used. Inventory was limited to production phase only which included raw material, energy input and transportation involved in production phase of fibres as input and the emission and waste or by-products during production of fibre. For data collection, companies were contacted individually to obtain product-based information for more precise data.

Life cycle impact analysis (LCIA) is the phase performed to provide additional information to assess the inventory data collected during LCI to obtain better understanding of the environmental impacts. This phase is conducted in all LCA but in few this phase is major as only inventory analysis would be carried out. All other phases in the system or product lifecycle would be excluded. LCIA would analyse all the phases involved in a product lifecycle to obtain impact caused by them. The case study presented in this thesis is LCIA where only the production phase of fibres and their inventory is analysed.

The final stage of LCA is discussing the results obtained by the analysis and concluding to help making recommendations or decision making as per the goal and scope of the study. LCA can be conducted based on Excel or software such as: Gabi, Sima-Pro which contain some of the existing data base like Eco-invent existing within the software. Based on the aim, analysis is performed and the resulted are then presented. Discussion of these results play a major role as the decisions are made based on this discussion if the product is environmentally friendly or not.

LCA is a powerful tool to assess the environmental impact, environmental performance and risk assessment and to help in decision making to choose better alternative among various products and services available. On the other hand, LCA cannot be used for all situations as it does not consider the economic and social aspect of the products or the services.

3.1.2 FRAMEWORK OF AN LCA

LCA is performed in accordance to guidance and requirements mentioned in ISO 14044 and ISO 14040. (43) (41)

GOAL AND SCOPE DEFINITION

The goal of an LCA defines the intended application, reason for conducting the study and the intended audience for the studies. The scope of an LCA is used to define the depth and detail of the study to meet the goals stated. The scope includes the format of the report, i.e. the way the analysis in presented. The goal defines the necessary outcomes to be reported after the analysis. The data requirements, considerations, assumptions, limitations and initial data requirement for conducting an LCA is defined based on the initial goal and scope of the study. The functional unit, system boundary and allocation procedures are defined based on the goals listed. Also, the impact categories selected, method of impact assessment and interpretation to be used and the type of critical review are all decided based on the goal and scope of the study. For this thesis, the goal was to select an environmentally friendly alternative for fibres to be used in shotcrete. With this as the aim, the scope of the work, the product system and the functions of the product system to be studied were limited to only analyse production of fibres. As per the goal, all impact categories were analysed, but for further calculation purposes, only the impact category called Global warming potential was considered in this study.

FUNCTIONAL UNIT

As defined in ISO 14040, (43) "the functional unit defines the quantification of the identifies functions of the product. The primary purpose of the functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results".

For example, for LCA of fibre, functional unit can be defined as "1 kilogram of fibre". Even for comparative LCA of fibres same functional unit can be used since they are similar entities. On the other hand, for comparative LCA on two different entities like a newspaper and a E-book, the functional unit is very difficult to be defined considering the fact that newspapers and e-books are different entities. Perhaps it can be defined as "the daily reading of one newspaper of 30 pages in a paper format and on an e-reader, during the lifetime of the e-reader, for one unique reader" which is very complex to understand.

SYSTEM BOUNDARIES

System boundaries are very important to be describes in an LCA as they define different life cycle stages to be included in the analysis. System boundaries define the unit processes to be included in the product system. A system boundary may be with respect to the geographical location, time frame, the input and output flows and impact categories to be included.

While setting the system boundary, it is important to consider the product system defined based on the goal and scope defined, assumptions made and to justify the cut-off criteria considered. System boundaries are defined based on the goal and scope of the analysis. It can be cradle-to-gate, which includes raw material, transportation and production phase or it could be cradle-to-grave which includes ever process, energy and material involved in production phase, use phase, and end life i.e., recycling phase. Based on different system boundaries assigned, collection of the data differs for the analysis.

This thesis presents, EPD of fibres from cradle-to-gate stage and the other phases like use phase and recycling phases are not considered. Also, initial extraction and treatment of raw materialist recycling of by-products and treatment of waste produced during manifesting of fibres are not considered. This forms one of the cut-offs criteria for the analysis.

3.1.3 LIFE CYCLE INVENTORY ANALYSIS

Inventory analysis refers to the collection of data regarding all the raw materials, processes and calculations to quantify input and output flow involved in the product system. During data collection, new limitations are learnt which modify the requirement and limitations of the study in order to meet the goal and scope of the study described. Hence, data collection is said to be an iterative process.

Input data related to various raw material, energy, ancillary inputs and other physical inputs are considered for each unit process with respect to the system boundaries set. Data collection also includes information regarding products, by-products, waste produced along with considering emissions into air, water and soil. Data collected is further linked to the unit process, reference flow and validated before proceeding with further calculation procedures. Different forms and sources of energy involved in the process must be considered accurately in order to calculate the energy flow for the product system defined. The data collected should be qualitative and quantitative and is collected for each unit flow in accordance with the goal and scope and the system boundaries defined. Quality of the data refers to the reference of obtained data, time, process of collecting the data or sometimes calculated data with the process of calculation explained

For the case study presented, most of the data related to production of fibres and their technical performance was obtained from literature reviews and from documents obtained from the companies. Further, to obtain the dosage of fibres, necessary laboratory tests were conducted by other group of researchers at the laboratory and the final values are only reported in this thesis. No details about the test processes are recorded in this thesis as the main aim is to study environmental impact of fibres.

3.1.4 LIFE CYCLE IMPACT ASSESSMENT

This stage of the LCA deals with evaluating the LCI results to identify the potential environmental impacts associated with the product system. LCIA is a relative approach based on the functional unit compared to other risk assessment or impact assessment techniques. LCIA is a well-coordinated phase of LCA. It coordinates among other phases of LCA in order to satisfy the data quality required to meet the goal and scope defined. This also takes into consideration all of the assumptions and system boundaries described along with various uncertainties involved. These uncertainties might be associated with the quality of data collected, cut-off criteria and allocations made.

ELEMENTS OF LCIA:

LCIA is separated into different elements that define each LCIA element clearly and to be included in the goal and scope definition and to conduct quality assessment of LCIA methods and make assumptions and other procedures within each element transparent for critical review and reporting purpose. The level of detailing and selection of unit processes, system boundaries, allocation depends entirely only on the definition of the goal and scope.

Mandatory elements of LCIA are shown in the flow chart given by (42):

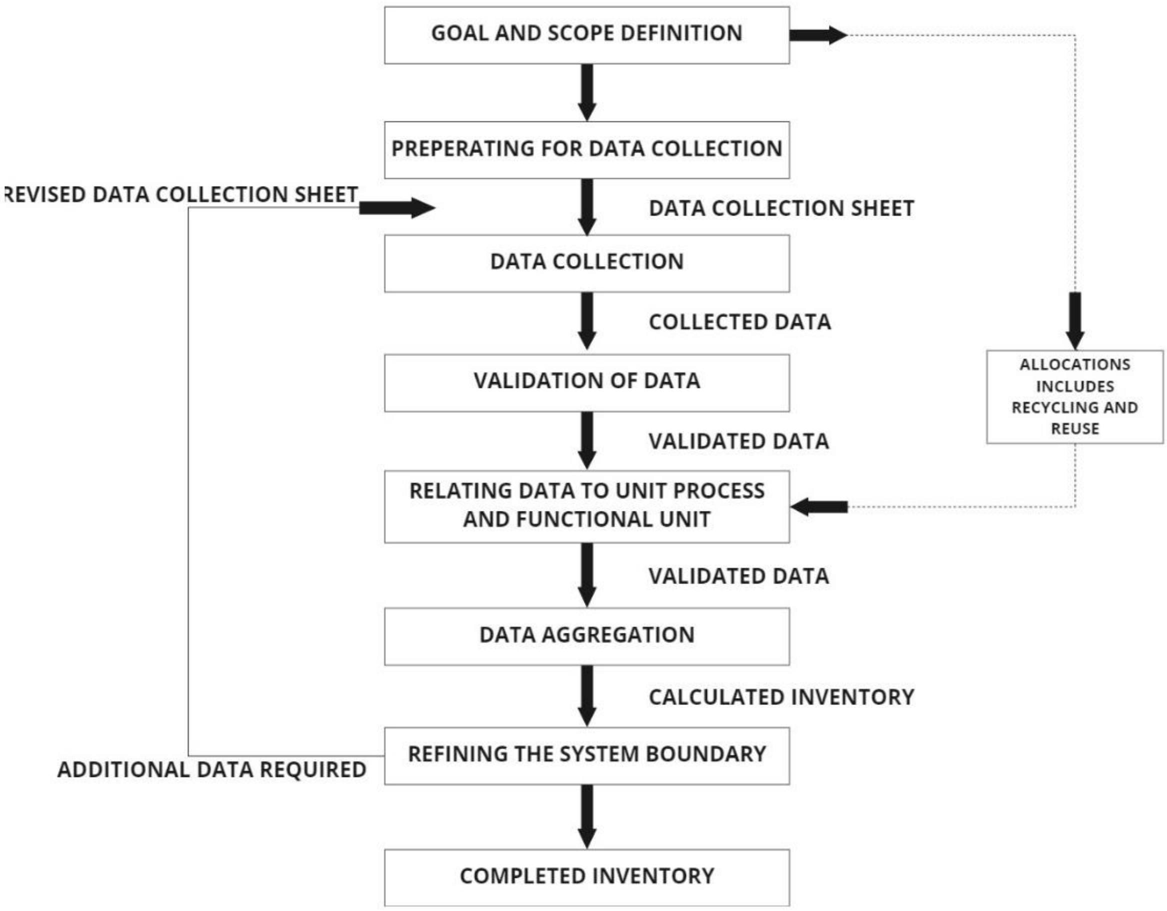

Figure 3.2: Flow Chart Showing Mandatory Elements of LCIA.

1. Selection of impact categories, category indicators and characterization models: (42) Impact categories, category indicators and characterization models selected should be in accordance with the goal and scope defined and should be justified by the system boundaries and allocations. They should also be consistent in defining the environmental issues to be focused as defined in the goal and scope. Most of the times, the existing impact categories are used. However, in some rare cases, new impact categories are defined as per the study requirement. In case of LCI results other than mass and energy flow data included in an LCA for example like the land use, should be identified and the relationship to corresponding category indicators shall be explained.

2. Each impact category should be defined with identification of category endpoint, definition of category indicator for given endpoints, assigning results to appropriate impact categories based on category endpoints selected, identification of the characterization model and the characterization factors.

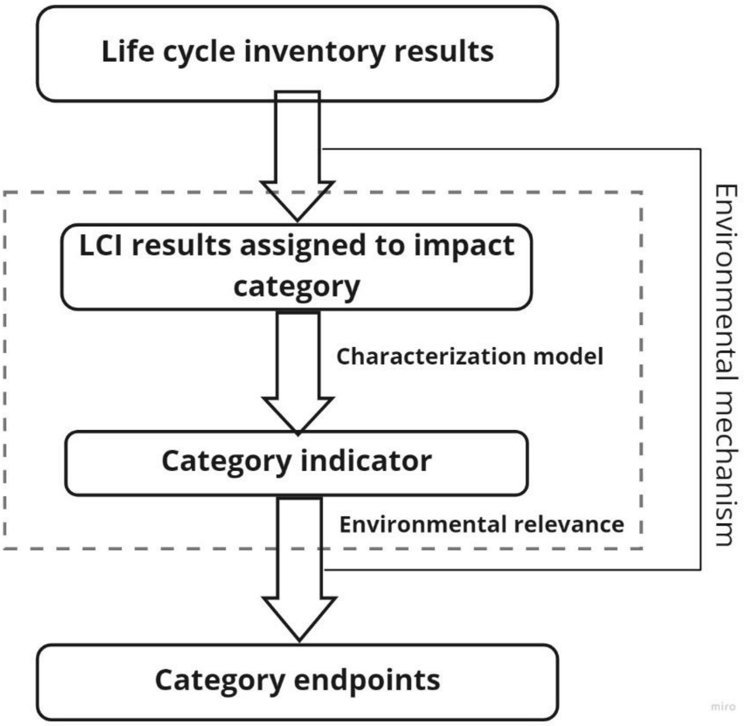

Figure 3.3: Concept of category indicators (41).

3.1.5 IMPACT CATEGORIES

The impact categories used to analyse the LCI are mainly categorised into two mainstreams that is the midpoint approach and the endpoint approach. There are various impact categories available for different product stages. But the most important ones considered for an EPD are listed below: (44) (45)

1. Global warming potential
2. Ozone depletion
3. Acidification of land and water
4. Eutrophication
5. Potential ozone creation
6. Depletion of abiotic resources - element
7. Depletion of abiotic resources – fossil fuels

Although the aim of this thesis is to discuss the fibres clearly only based on global warming potential, it is also important to consider the other environmental impact categories in the EPD. Hence, a few of the results from the EPD are presented in tables 5, 6 and 7 are discussed in the results. The acidification potential (AP) indicator gives the of level of acidic gases being released into the atmosphere during the production of the fibres. These gases in combination with water in the atmosphere, leads to acid rain which causes severe damage to the ecosystem. Stratospheric ozone depletion (ODP) indicates the level of ozone depleting gases for e.g., CFC's (Chlorofluorocarbons), HCFC's (Hydrochlorofluorocarbons) which cause damage to the ozone layer resulting in depletion of the ozone layer. Eutrophication potential (EP) indicates the level of nitrates and phosphates which enter water from the effluent's releases from the production plant. These eventually accumulate in water bodies destroying the ecosystem of the water body gradually.

3.1.6 LIFE CYCLE INTERPRETATION

Life cycle interpretation is the phase of LCA where the results of the LCIA or LCI are discussed and interpretation of the results are carried out with regards to the goal and scope of the study defined. The results should identify potential environmental impacts and help to make recommendations to the intended audience and decision makers. Interpretation involves an iterative process of reviewing the results along with the quality of the data collected to provide understandable, complete and consistent results.

Life cycle interpretation consists of several elements described by (41) such as:

- identification of significant issues based on the results of LCIA or LCI analysis
- a complete evaluation considering sensitivity and consistency
- conclusions, limitations, and recommendations.

Figure 3.4, below shows the relationship between elements within interpretation phase with other LCA phases (41)

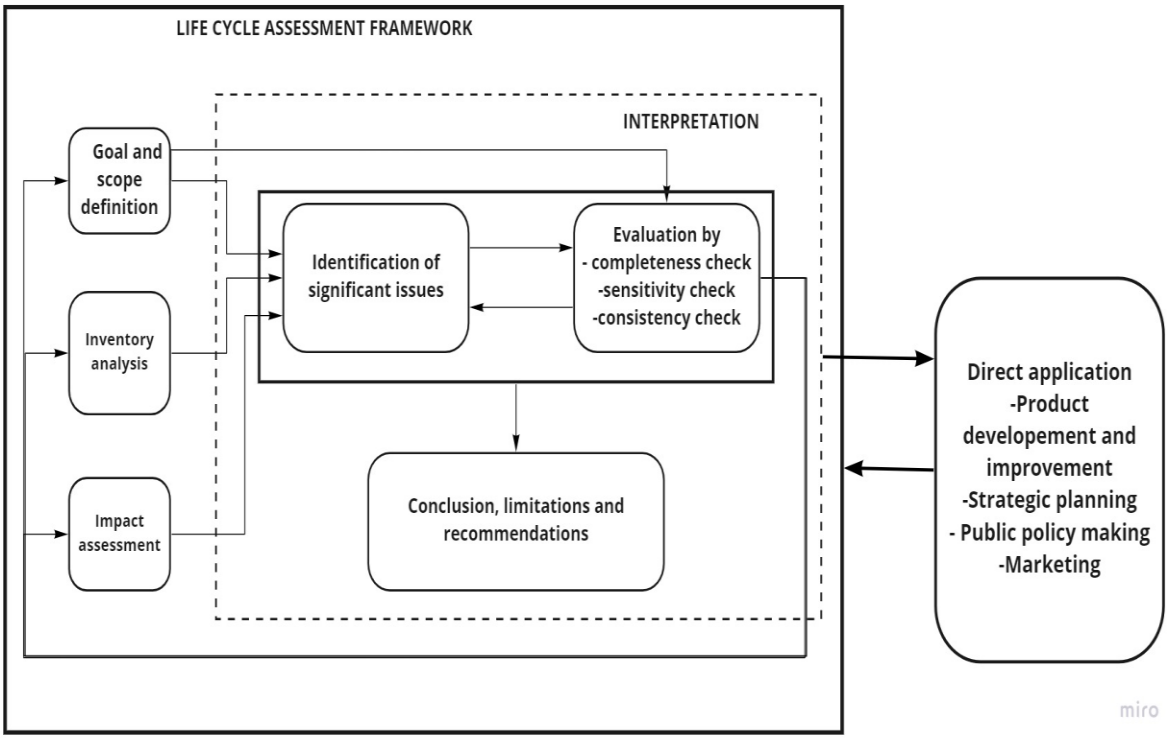

Figure 3.4: Relationship between elements within interpretation phase with other phases of LCA.

3.2 ENVIRONMENTAL PRODUCT DECLARATION

Over the last few years, with the construction industry focusing on climate neutral material and substances, the interest for environmental declaration in building rating and certification scheme has increased. This is because they help in providing a clear demonstration of the life cycle and the environmental impact at different life cycle stages of a product or service. Environmental product declaration (EPD) plays an important role in such building schemes along with providing a fair comparison based on the environment performance of the products and services. EPDs help in eco-design when a new product is being developed. EPD's help in comparing and buying low-carbon products, use in LCAs to enable building level LCAs and in documentation of use of products with an EPD in a project. Also, by using EPDs, an organisation can identify, examine, monitor and control the environmental performance. They help in the sustainable supply chain development and development of circular economy. Till date, it has not been made mandatory by law for the manufacturers to provide EPD but with increasing market regulations it is highly recommended to provide one. LCA comparison on product, assembly and building level is a common practice in the construction sector due to lack of specific product based EPD and this this aims to provide an EPD based product comparison of environmental aspects of fibres (46). In Sweden, the Swedish transportation authority encourages to use product based EPDs to evaluate the climate performance of the services and materials. Also, some of the government procurement of projects in few municipalities in Sweden and in the international building assessment schemes demand for product based EPD. At present the manufacturer and client are encouraged to have EPD to assess the climate performance of the project but it is very important to encourage the middle point of communication between client and manufacturer i.e., the contractor to use EPD to verify their project in order to achieve the climate reduction goal set for Sweden. Use of EPDs has several other advantages like saving in cost by achieving multiple customer requirement, help in selection of material and products based on their environmental performance, help in winning of projects during bids with EPDs and to be able to work on strategies to improve internal performance of company by using more climate neutral material and in finally achieving the EU requirements of climate performance in infrastructure projects.

The core product category rules (PCR) are provided by EPD operators stakeholders. These are provided for Type III environmental declarations for construction services and product that is compliant with ISO 14025 standard. Type III EPD is with third -party certification, including external verification and considering manufacturer as participant only by the program operator. The core of PCR is to define life cycle stages that are considered for a product in EPD, define various indicators to be declared, rules for calculating life cycle inventory and impact assessment. Along with this it also defines conditions under which different construction products may be compared based on the EPD. According to standard EN-15804, an environmental product declaration (EPD) is a document which provides scientific based quantified, environmental related information associated with construction product or service. An EPD is a declaration of the environmental performance of a product or service. This document also consists of comprehensive report of the background LCA.

EPD is a comprehensive report including LCA developed for a product or service. It plays prominent role in identifying the best product and service to be used in the construction sector which leads for the less stress to environment in terms of emission to air, water and soil along with considering information related impact on health throughout different construction phases (45).

3.2.1 TYPES OF EPD

In an EPD, to identify various impacts on environment and assess the construction products, various modules are defined which consider different stages of the life cycle of the product. These modules are given names like modules A1-A3 for production stage, modules A4-A5 for construction phase, modules B1-B7 for use stage, modules C1-C4 for end-of-life stage and module D for benefits and loads beyond the system boundary. EPDs are identified as different types based on the modules being considered for that particular product or service. Certain product and services might be exempted from declaring end life stage and module D if they provide proper explanation and information regarding where to find the scenarios for end-of-life modules. Also, in some cases the goal of the study would only be to study certain stages of the product like the case study presented in this thesis considered only the production stage which is modules A1-A3.

Types of EPD:

1. cradle to gate with modules A1-A3, C1-C4 and D which is the default type of EPD based on declared unit.

2. cradle to gate with modules A1-A3, C1-C4 and D along with other additional modules like A4 or A5 or B1-B7. This EPD is based on a functional unit or declared unit.

3. cradle to grave and module D i.e., all modules under A, B, C and D which are based on a functional unit or declared unit.

4. cradle to gate which contains minimum modules to be declared i.e., module A1-A3. It applies to products exempted from declaring modules C and D and is based on a declared unit.

5. cradle to gate which contains A1-A3 modules along with additional module like A4 or A5 and is based on functional unit or declared unit.

The chart below in figure 3.5 describes various types of EPD's based on the modules considered under each type and the life cycle stage considered under various modules (45).

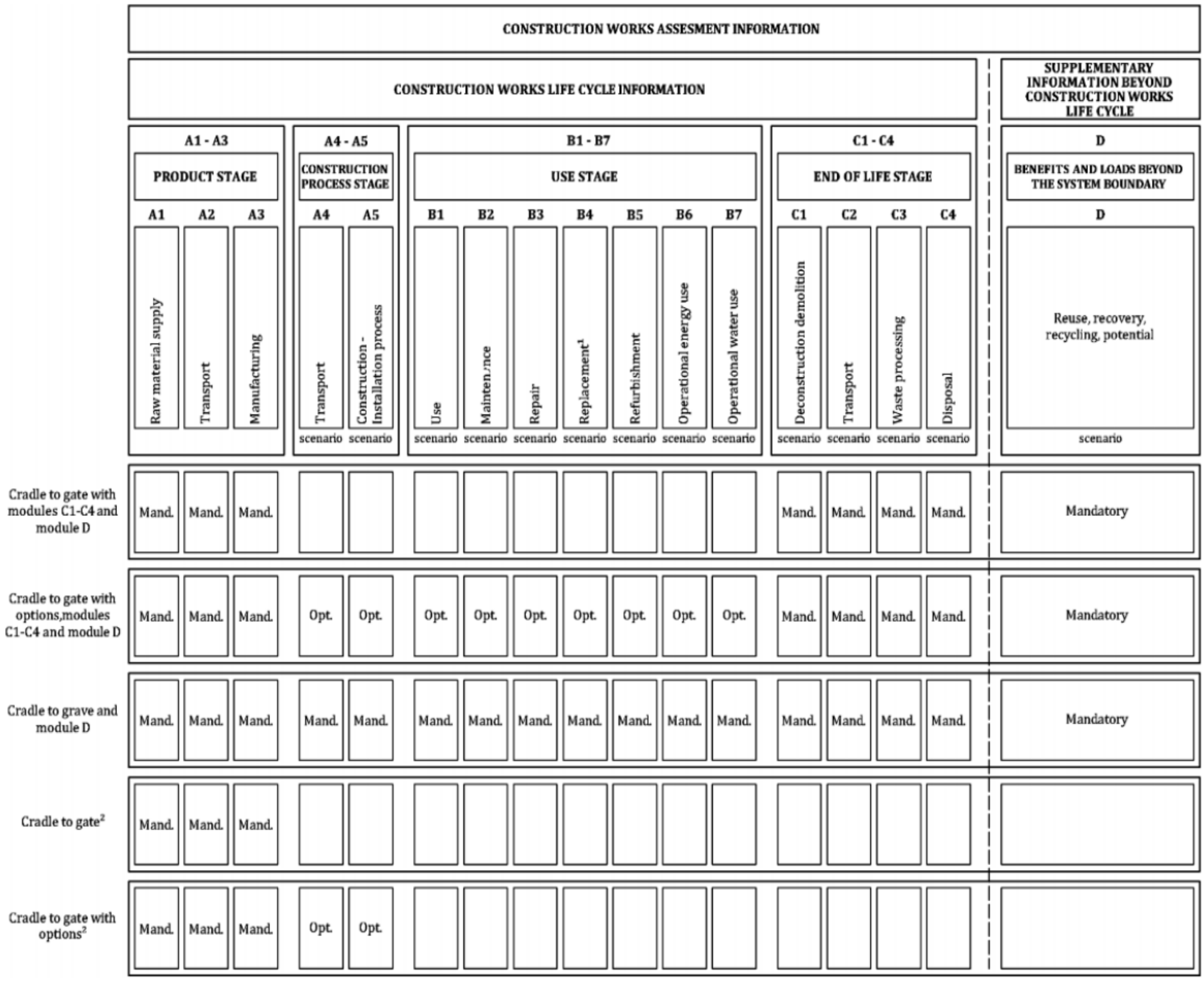

Figure 3.5: Types of EPD from EN-15804 (45).

Comparability of EPD for construction products: Construction products are compared based on the EPD information to assess environmental performance of the products. The comparison is made by considering the complete life cycle of the product at a sub-building level like for assembled systems, components, products for one or more life cycle stages.

Ownership, responsibility and liability for EPD: For the construction products or services the complete liability and ownership of EPD lies in the hands of a manufacturer.

Communication formats: The EPD shall have communication format in accordance with EN 15942, sustainability construction works - Environmental product declarations - Communication formats: business to business.

3.2.2 Content of the EPD

An EPD should contain some of the general information regarding the name, address of the manufacturer, declared functional unit, date of declaration and validity of 5 years to the EPD, product specification with a simple visual representation of how it relates to intended construction product or service. Along with this, it should contain information regarding the name and address of the certifier along with the program used to carry out certification. If the EPD is based on LCA then the information regarding the product stages covering life cycle is necessary. Most importantly an EPD should contain information on technical performance so that the comparison of the environmental impacts is done for the products with similar technical performance.

An EPD shall contain the various life cycle stages for a product life cycle represented in a simple flow chart according to the information from LCA. These product stages and processes of LCA were explained in this chapter previously. An EPD consists of two key documents, one is based on LCA information which is not for public and the other is public document which consists of the results.

VALIDATION OF AN EPD

An EPD is valid for 5 years from the issue date and needs to be reviewed and verified after this period. If there is no change in the underlying data, then there is no need for recalculation after 5 years. But if there is an update then a reassessment of the data is necessary. The process for verification and validity of EPD is explained by the standards EN ISO 14025 and ISO 21930.

3.3 Literature review of LCA

OVERVIEW OF AVAILABLE LITERATURE

Although LCA is the most important process to be followed and is given a lot of priority in the present days to make life more sustainable, LCA regarding fibres and shotcrete are not widely available. Hence some of the LCA used as reference to obtain general idea about the process, assessment method and interpretation of results are presented in this section. Also, previously a lot of studies used complete LCA study to compare environmental impacts of product. Nowadays, EPD's are used to compare the products which are provided by the manufacturers of the product which helps in saving a lot of time and eliminates the process of conducting LCA.

Stoiber (47) conducted a cradle to gate LCA for Carbon fibre reinforced polymer (CFRP) for concrete structures. They considered the product phase of the material and were taking into account and provided estimated values of environmental impact by three impact categories which are global warming potential (GWP), acidification potential (AP) and abiotic depletion of fossil resources (ADPF). They concluded by justifying CFRP to be environmentally better alternative in bridge design, provided that design aims to optimally utilise the maximum strength and stiffness properties. The major drawback in this work was the inconsistent results and limited information due to which they did not consider ozone depletion potential impact category.

Ingrao (48) analysed entire input inventory for a precast reinforced concrete shed following ISO standards 14040:2006 and 14044:2006. Calculations were made in 7.3.3 version SimaPro accessing the Eco invent v.2.2 database. Analysis considered all the resources, material, input energy and transport involved which was given by the Firm producing the shed. Major drawback in this study was the data availability as collecting data was difficult from different sources involving various stakeholders. Also, data collected was not quality enough due to uncertainties involved. Some assumptions and hypothesis were made in order to suit the Eco invent database available.

Madoc (49) carried a comparative LCA of four different reinforcements for of concrete. The alternatives considered were producing steel reinforcement mesh, producing virgin polypropylene (PP) fibre, recycling industrial PP waste and recycling domestic PP waste which were studied from cradle to gate phase. All the processes involved in manufacturing, recycling, reprocessing along with transportation were taken into account for the analysis in detail. Results from this study showed that industrial recycled PP fibre were able to decrease the carbon dioxide equivalent with 50% compared to the virgin PP fibre. And, when compared to the steel reinforcement mesh, industrial PP can save 93% of CO2 equivalent. Along with this EPD's obtained by different manufactures of steel, basalt and synthetic fibres were considered which will be presented in next section

DRAWBACKS

The major drawback with the literature review is that finding specific work needed for the topic of thesis was not found and the ones available closest were referred to. The literatures available also had some drawback such as: insufficient data to support the conclusion, uncertainties, poor or low data quality. Along with this most of the work fail to explain and justify some of the assumptions and considerations made.

Along with these one of the major drawbacks is that no product-based life cycle is available with precise information regarding environmental performance of shotcrete or fibres.

KEY WORDS USED FOR LITERATURE SEARCH:

LCA, LCA of steel fibres, LCA of concrete, LCA of basalt fibres, LCA of synthetic fibres in concrete, Comparative LCA of fibres in shotcrete, EPD of fibres, LCA of fibres in concrete, Environmental impacts of fibres, Micro fibres in concrete, Environmental analysis of fibres.

Chapter 4

METHOD

4.1 CASE STUDY

INTRODUCTION TO THE PROJECT

A major transport infrastructure project named West Link is being carried out in Gothenburg, West Sweden. This project is a railway connection in a tunnel under the centre of Gothenburg which will connect the commuter rail services to routes that pass through the city with three new stations. The West Link project was proposed in the national plan for Swedish Transport System 2014-2025, which was adopted by the government in 2014. The West Link is an eight-kilometre-long double lane railway track along with six-kilometre railway tunnel, beneath the city. The project is estimated to be completed by the year 2026.

In this case study, the shotcrete for the rock support for one part of the tunnel is being focused on. Two alternative design methods are used to obtain the design for the shotcrete rock support for the tunnel. One is based on the Q-method and the other one is the analytical method. For each design method, a suitable dosage of steel, basalt and synthetic fibres were suggested. The environmental impact of each fibre type was then calculated based on collected EPD's. The major focus in this thesis is life cycle assessment of different fibre types i.e., steel, basalt and synthetic fibres for the shotcrete and to suggest better alternative in terms of global warming potential.

4.2 EPD COLLECTED

EPDs which are published at operator's websites are the only EPDs considered as right ones according to the EPD-system rules. A document called be an EPD only if it has been third party reviewed and accepted to be published by one of the EPD operator. Environdec in Sweden (50), EPD in Norway (51), IBU in Germany (52) etc., are some of these operators. The manufacturers of fibres had product based EPDs available on the website, which were the source of ready data for our project. This made it easier to obtain the required information regarding the life cycle of the fibres. Some of these EPD's contained detailed information about functional unit, system boundaries, allocations being clearly explained while, some of them lacked the required explanation to justify their assumptions with respect to source of energy input and recycling of waste and by-products. The detailed information regarding allocation of waste products and system boundaries with respect to transportation of materials were not estimated in detail for few cases and it was just modelled based on existing eco-invent database without proper justification. For a case study this could be feasible way to use data from eco-invent, but for product-based data from producers, a much-detailed information and explanation would make it more understandable. Upon careful assessment and studying, EPD's for each fibre type were selected to extract further required information. These EPD’s selected to study contained stages A1-A3 of the product clearly presented in a structured manner along with proper justification for all the considerations and allocations made. They also presented documented results according to the ISO standards for EPD.

All the information collected from EPD's are tabulated below:

Table 2 : EPD data for steel fibres:

	Unit	Bekaert	Arcelormittal	MAPEI
Product		Dramix 3D,4D,5D	Type III ITB	DE 35/0, DE 50/0, DE 50/1
Validity	year	2021 - 2026	2017- 2022	2017 - 2022
GWP [A1-A3]	kg CO_2eq.	0.88	0.77	0.77
Functional unit	kg of fibre	1.0	1.0	1.0
System boundaries *				
Production Stage		A1-A3	A1-A3	A1-A3
Transportation to site		-	A4	A4
Construction Stage		A5	A5	-
Usage stage		-	B1-B7	-
End of life stage		C1-C4 along with module D	C1-C4 along with module D	
Allocations		Product mass based	Product mass based	Product mass based

*refer to the figure 3.5 Types of EPD from EN-15804 in previous chapter.

Since Basalt fibres are relatively new in the market, only one EPD could be obtained and is presented below.

Table 3: EPD data for Basalt fibres:

	Unit	ReforceTech
Product		Basalt MiniBar
Validity	Year	-
GWP [A1-A3]	kg CO_2eq.	2.61
Functional unit	kg of fibre	1.0
System boundaries * Production Stage Construction Stage Usage stage End of life stage		 A1-A3 - - -
Allocations		-

*refer to the figure 3.5 Types of EPD from EN-15804 in previous chapter.

Table 4: EPD data for Synthetic fibres:

	Unit	BarChip	FIBERCON	ADFIL construction fibres	Contec Fibre AG
Product		BarChip R50, R65, R54, R60	SMP65 - SHOTCRETE	DURUS EASYFINISH	CONCRIX FIBER
Validity	year	2020-2025	2016-2021	2020-2025	2017-2022
GWP [A1-A3]	kg CO_2eq.	1.80	4.8	1.95	4.16
Functional unit	kg of fibre	1.0	1.0	1.0	1.0

System boundaries *					
Production Stage		A1-A3	A1-A3	A1-A3	A1-A3
Transportation stage		-	-	A4	-
Construction Stage		-	-	A5	-
Usage stage		-	-	-	-
End of life stage				C1-C4 along with module D	
Allocations		Product mass based	Product mass based	Product mass based	Product mass based

EPD of fibres consist the results presented for various impact categories related to environment impact, resources used, waste production and output flows. This report consists of the results presented for few of the impacts under environmental categories.

Table 5: EPD results for steel fibres:

		Arcelormittal	**MAPEI- steel fibre DE 35/0, DE 50/0, DE 50/1**	**BEKAERT - Dramix steel fibres**
INDICATORS	**UNITS**			
GWP	**kg CO_2 eq.**	**0.77**	**0.77**	**0.88**
ODP	kg CFC_{11} eq.	0.1E-03	8.22E-08	4.7 E-08
AP	kg SO_2 eq.	1.0E-03	1.41E-03	3.45E-03
EP	kg PO_4^{3-}eq.	0.3E-03	3.97E-03	2.86E-03

Table 6: EPD results for basalt fibres:

		Reforcetech - Basalt Minibar
Indicators	**Units**	
GWP	**kg CO_2 eq.**	**2.61**
ODP	kg CFC_{11} eq.	2.80E-07
AP	kg SO_2 eq.	1.05E-02
EP	kg PO_4^{3-}eq.	9.89E-05

Table 7: EPD results for synthetic fibres:

		BARCHIP	**CONTEC FIBER AG**	**FIBERCON**	**ADFIL construction fibers**

Indicators	**Units**				
GWP	**kg CO_2 eq.**	**1.8**	**4.16**	**2.50**	**1.95**
ODP	kg CFC_{11} eq.	2.23E-13	7.74E-08	8.80E-09	1.12E-09
AP	kg SO_2eq.	7.99E-03	1.07E-02	2.30E-03	4.10E-03
EP	kg PO_4^{3-}eq.	8.95E-04	1.13E-03	6.50E-04	5.49E-06

*GWP- total global warming potential, ODP-Potential for stratospheric ozone depletion, AP-Acidification potential for sources on land and water, EP- Eutrophication potential.

4.3 DESIGN OF SHOTCRETE

For our case study, for the Project Centralen, the design will be performed in two different ways: an analytical design method that defines required residual flexural strength and an empirical design method that defined requirements on the energy absorption. All the information regarding the design was obtained from the design team of the project.

4.3.1 CASE 1 - AIM TO REACH RESIDUAL STRENGTH 3 MPa

The Q-method is used to determine the required shotcrete thickness and maximum distance between the rock bolts which ensured overall stability of the tunnel. However, the recommended energy absorption of the shotcrete given by the Q-system is not used to specify the requirements of the shotcrete. Instead, a minimum residual flexural strength is specified as the structural requirement for the shotcrete as the structural capacity is often verified. In particular the residual flexural strength is used to determine the moment capacity of the shotcrete which in turn is used to verify the load carrying capacity of the shotcrete. The shotcrete should be able to carry the load from the loose blocks that fits between the rock bolts. According to the design requirements stated by the team, the characteristic residual strength for fibre-reinforced shotcrete should be equal to 3.0 MPa while the design residual strength should be equal to 2.2 MPa. The deformation class for shotcrete to satisfy was not stated in the design i.e., at what vertical displacement the residual strength should be reached. Normally, the shotcrete is classified as DxSy where x is the vertical deformation as “y” is the corresponding residual strength. For this project since this was not stated, the deformation class was assumed to be class D2 which yields that the shotcrete is D2S3 meaning that the shotcrete should have a residual strength of 3 MPa when the vertical deformation is between 0.5 and 2.0 mm when tested according to EN-14488-3.

In this case, we aim to design shotcrete to reach residual strength of 3 MPa at 2.0 mm deflection according to EN 14488-3. Design with three different fibre alternative which are steel, basalt and synthetic fibre will be calculated and compared with respect to global warming potential to know better design alternative of the fibre type and the required dosage.

4.3.2 CASE 2 - AIM TO REACH 200 JOULES

In this case, fibre-reinforced shotcrete is designed based on the Q-system. Three different fibre types were compared; steel, synthetic and basalt fibres with the aim to reach 200 Joules at 40 mm displacement RDP test. Here, all of the alternatives shall fulfil a required energy absorption that is measure on square or round panels. In this thesis, we will assume that we a good quality rock and that the energy absorption of the shotcrete should be 200 Joules.

Correlation between RMR and the Q-value:

Q-chart gives a direct relation between the Q-value and the support of the tunnel as shown in the chart below figure 4.2. In this case, two different supports Type 1 and Type 2 were designed. This design was carried out based on the distribution of RMR and Q for the entire tunnel which is determined by the excavation support ratio (ESR) which was equal to 1 and the effective span for the roof was 14.3 m. These are pre-designed support systems which will be designed before excavation of the tunnel and be used if the rock conditions are same as predicted.

In our case, we will use Type 2 since this is the dominate support type and we will only consider the support of the roof. The design of the support based on the Q-system is shown in figure 4.1.

$$RMR = 9\ln(Q) + 44 \qquad \text{eq (4.1)}$$

Table 8: Distribution of basic RMR and corresponding Q-value according to equation.

Distribution (%)	RMR	Q	Support
19	81-100	61-504	Type 1
81	61-80	7-55	Type 2

Table 9: Suggested rock support with respect to structural capacity based on the Q-method.

Support	Q_{max}	Q_{min}	Q_{mean}	t_s[mm]	E_{EF}[J]	l_b[m]	c_b[m]
Roof 2	55	7	31	50	500	4.0	2.6

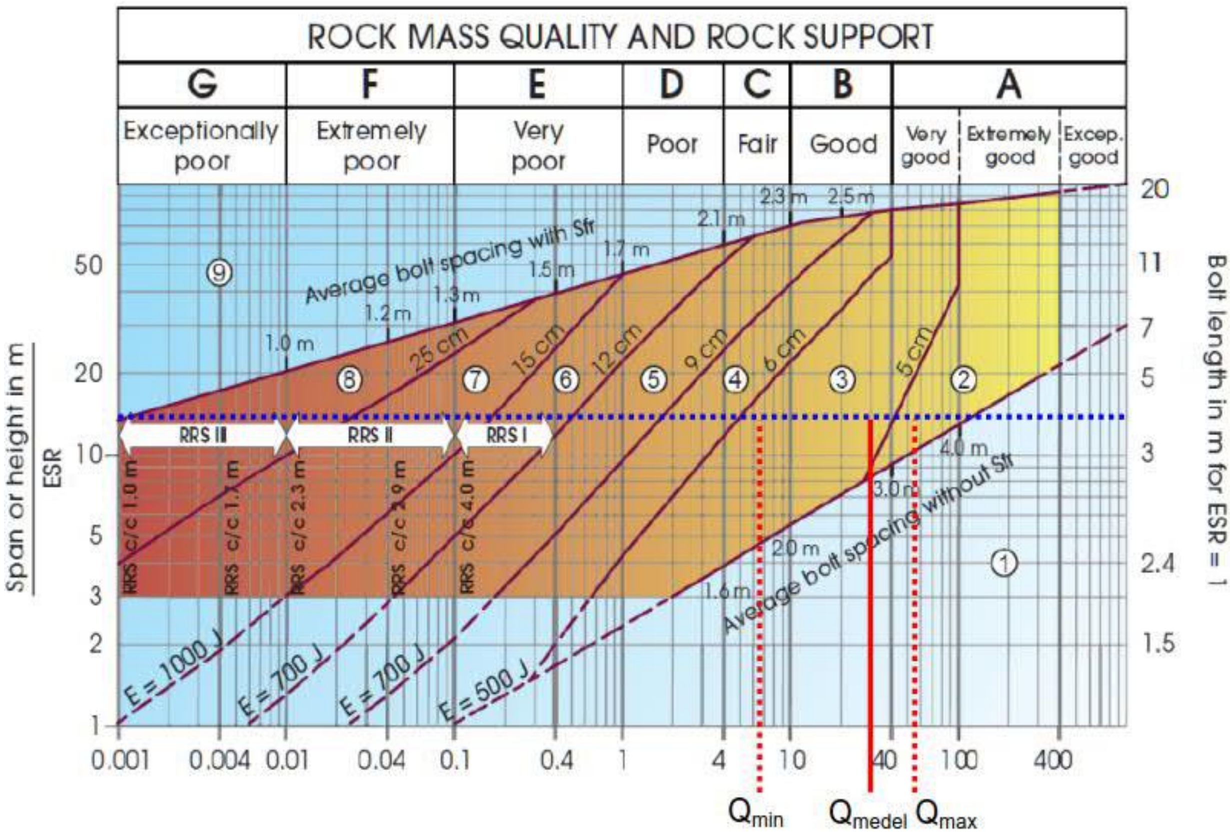

Figure 4.1: Design of type 2 support based on the Q-system.

4.3.3 LABORATORY TESTING OF FIBRES

Laboratory testing was carried out to determine the residual flexural strength and the energy absorption for each fibre at different dosage. Testing was performed as per the standards at Vattenfall R&D in Älvkarleby, Sweden by accredited personnel. In order to understand the effect of different dosage, each fibre was tested with 3 different fibre dosage. Basic concrete mix presented in Table 10, was tested. All the test specimens were cast in laboratory as per standard procedure and were tested after minimum of 28 days. 3 samples of each type were subjected to testing. The residual strength was tested through four-point bending according to EN 14488-3, energy absorption was tested based on ASTM C1550, while compressive strength was tested according to EN 12390-3. The fibres tested are shown in the figure 4.2 below and the test results obtained for residual strength and energy absorption are presented in next section. (50).

Table 10: Concrete mix tested in laboratories.

Material	**Units**	**Quantity**
Cement	kg/m^3	500
Water	kg/m^3	204
w/c	-	0.41
Aggregate 0-2 mm	kg/m^3	489
Aggregate 0-8 mm	kg/m^3	1141
Release $agent^1$	kg/m^3	1.6
Plasticizer^2	kg/m^3	5.0
Air^3	%	4.5-5.1
Slump^3	mm	80-160

1 Sika Perfin 301, 2 Sika Visco − crete 6730, 3 Given as a range for all samples

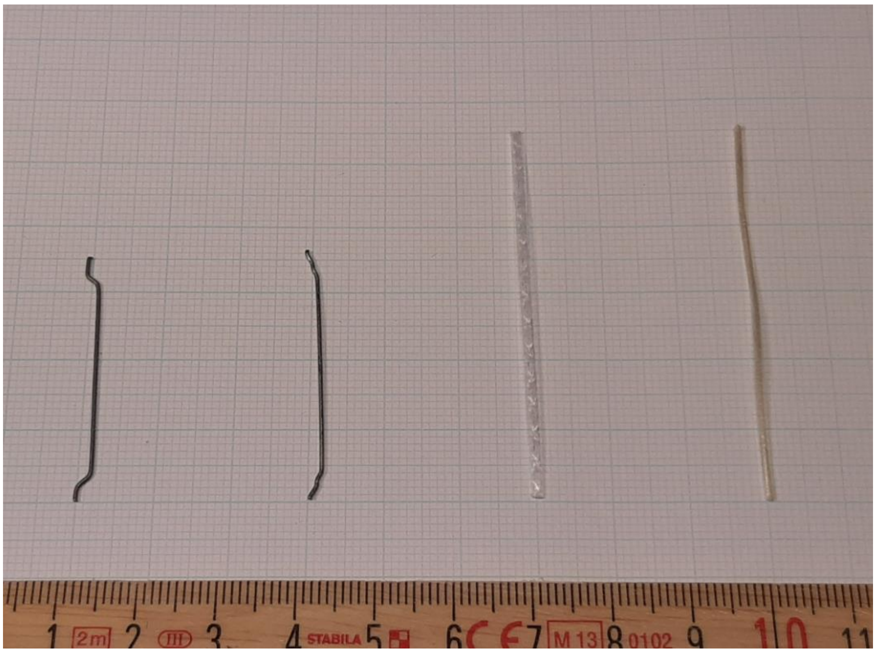

Figure 4.2: Fibres used for testing in laboratory (50).

Chapter 5

RESULTS AND DISCUSSION

5.1 RESULTS FROM STRUCTURAL TESTING

Table 11: Results from structural testing of fibre-reinforced shotcrete:

		Cubes	Beams EN 14488-3		Panels ASTM C1550
Fibres	**Dosage [kg/m3]**	**fc [MPa]**	**fr2 [MPa]**	**fr2, mean [MPa]**	**E40 [J]**
Dramix 3D	50	57/63/64	5.1/5.2/6.8	5.7*	709/764/724
	40	60/63/65	2.9/3.2/5.7	3.9*	592/597/792
	30	56/61/63	2.8/2.8/5.0	3.5*	472/516/564
Dramix 4D	50	57/57/59	5.6/6.9/7.5	6.7*	737/957/979
	30	58/59/62	3.4/4.4/4.9	4.2*	476/825/927
	20	59/61/61	1.7/2.4/4.0	2.7	577/583/653
Basalt MiniBar	20	58/62/64	4.3/4.8/5.4	4.8*	475/536/557
	16	63/63/64	2.8/3.7/5.2	3.9*	379/511/644
	14	63/63/64	2.0/2.7/2.9	2.5	362/503/514
BarChip 56	9	55/55/57	2.1/2.6/2.7	2.5	703/736/806
	6	55/61/64	1.8/2.5/2.8	2.4	558/610/662
	3	49/51/54	1.3/1.4/1.5	1.4	202/233/272

*Indicates tests that fulfil the requirement.

The resulted obtained by testing of concrete specimens with different fibres for different dosages are shown in the Table 11. Concrete beams, cubes and panels were reinforced with steel, basalt and synthetic fibres each with 3 different dosages to understand the effect of fibre volume on the strength of concrete. Furthermore, an average of three beams tested for each fibre type was considered to obtain a mean value for residual strength. The target flexural strength was 3 MPa as per the requirements. To achieve this, the mean value of the test series must be higher than this and each individual sample must have a residual strength of at least 80% of 3 MPa which is 2.4 MPa. Similarly, the requirements with respect to the energy absorption is 200 J. To achieve this, two out of the three test specimens must have a energy absorption of 200 J.

Table 1210: Calculated GWP values for the tested dosages:

		Beams EN 14488-3	Panels -ASTM C1550	GWP of fibres [kg CO_2 eq.]	
Fibre	**Dosage (kg/m^3)**	**fr2, mean (MPa)**	**E40, mean (J)**	**per kg of fibres**	**per required dosage**
Dramix 3D	50	5.7	732	0.88	44
	40	3.9	660	0.88	35.2
	30	**3.5**	**517**	0.88	**26.4**
Dramix 4D	50	6.7	891	0.88	44
	30	**4.2**	**743**	0.88	**26.4**
	20	2.7	604	0.88	17.6
Basalt MiniBar	20	4.8	523	2.61	52.2
	16	**3.9**	**511**	2.61	**41.76**
	14	2.5	460	2.61	36.54
BarChip 56	9	2.5	748	1.8	16.2
	6	2.4	610	1.8	10.8
	3	1.4	236	1.8	5.4

As seen by the laboratory results, steel fibre for both Dramix 3D, and Dramix 4D are tested for 3 different dosages of fibre by volume and it is seen that for all the three dosages, the required flexural strength is achieved. For both Dramix 3D and Dramix 4D, 30 kg/m^3 seems to be optimum dosage to achieve the required residual flexural strength. While Dramix 4D achieves higher strength compared to Dramix 3D as they are more efficient. If you compare the energy absorption between 3D and 4D, we see that the 4D is more effective when the same dosage is used, see Figure 5.1. This is also true in the case of a residual strength at 50 kg/m^3 dosage. Also, it is observed that with smaller increase in the fibre dosage there is a larger increase in strength achieved for both steel fibres when compare with other fibre types. In accordance to the GWP calculated, for the required strength to be achieved, it is seen that steel fibres with optimum dosage of 30 kg/m^3, Dramix 3D and 4D causes lesser impact in comparison to other fibre types without the effect of concrete taken into consideration.

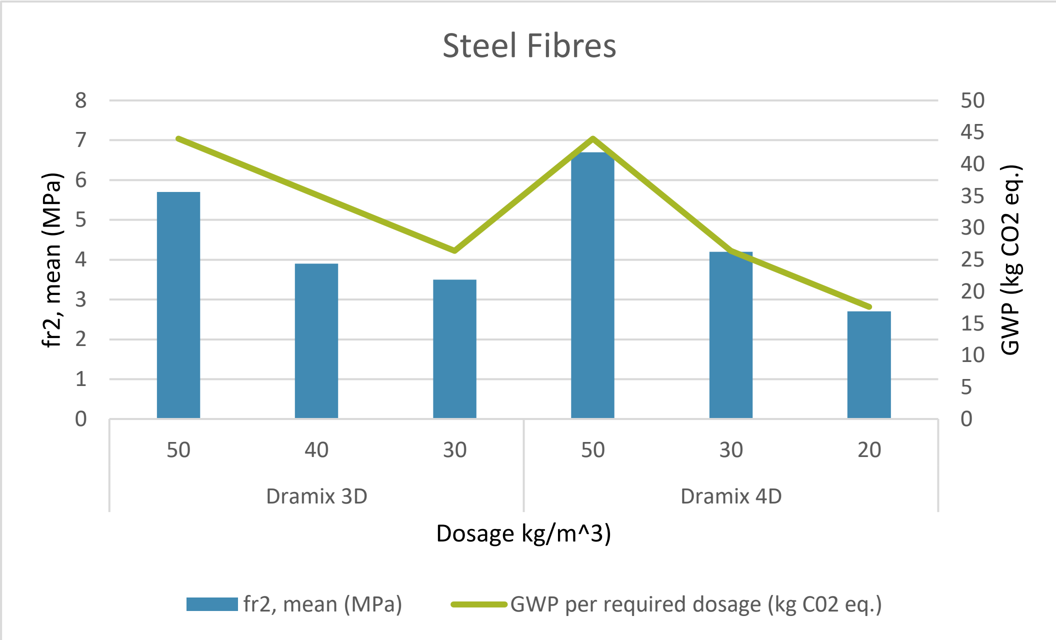

Figure 5.1: Results of flexural strength and GWP for steel fibres.

In the case with basalt fibres, we can see the required flexural strength is achieved at a dosage of 16 kg/m^3 and the required energy absorption is achieved at a dosage of 14 kg/m^3. The carbon emission per kilogram of basalt fibre is higher compared to steel fibres. But a lower dosage of basalt fibres could be used to achieve required strength. However, in the end the carbon emission will be lower for the shotcrete reinforced with steel fibres compared to basalt fibres.

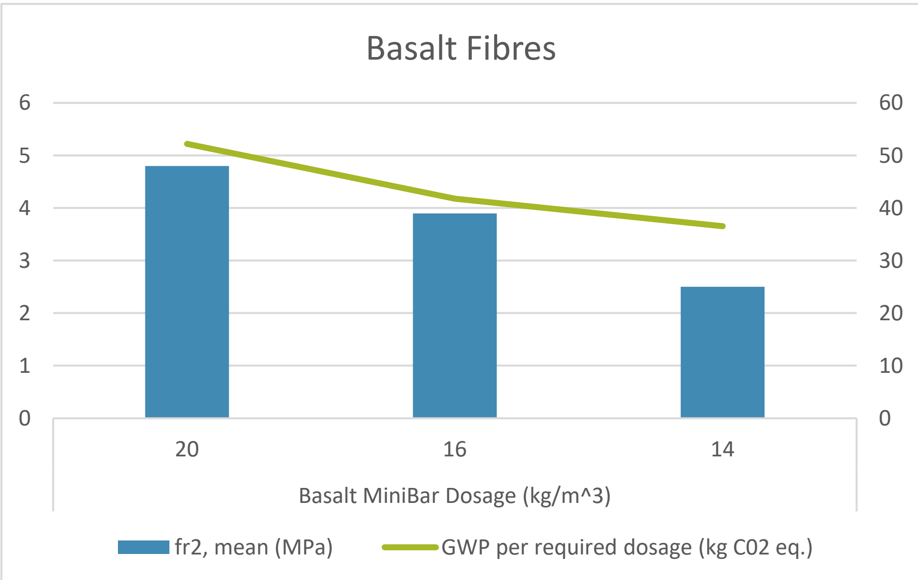

Figure 5.2: Results of flexural strength and GWP for basalt fibres.

In case of synthetic fibres, we see that with small increase of fibre volume, the strength achieved is higher as compared to steel fibre which is because the density of synthetic fibres around 900 kg/m^3 is significantly lower compared to steel with 7800 kg/m^3. We see that 40 kg/m^3 steel fibre is 0.5% by volume of fibres per cubic meter of shotcrete. For synthetic fibres of 0.5% by volume per cubic meter of shotcrete accounts for lesser mass of fibres which is 4.5 kg/m^3. Hence 40 kg of steel fibres can be replaced by 4.5 kg of synthetic fibres to achieve same volume of fibre dosage. As seen by the results the required flexural strength is not achieved by any dosage of fibres tested. However, it is likely that the required residual flexural strength can be achieved by increasing the dosage of fibres. The scatter in the results is unfortunate as testing of only 3 specimens were carried out due to various constraints. But ideally, synthetic fibres should be the optimum choice with respect to GWP taken into consideration that required strength can be achieved with smaller dosage of fibre. Just to give an idea of this, with 9 kg/m^3 of fibres, the strength achieved is 2.5 MPa with 16.2 kg CO_2 eq. which if compared to the optimum dosage of Dramix 3D steel fibres as per this experiment having achieved 3.5 MPa with dosage of 30 kg/m^3 we see that the GWP total is 26.4 kg CO_2 eq. Hence, if the dosage of synthetic fibre could be increased further, say around 3 kg/m^3, we can estimate to achieve required strength of 3 MPa with the GWP value still being lesser than that of steel fibres. So ideally synthetic fibres should be a better alternative among the three alternatives according to the study presented here.

The estimation of the dosage of synthetic fibre dosage is explained below. For a dosage of 30 kg/m^3 steel fibres, GWP is 26.4 kg CO_2eq. Similarly, GWP of synthetic fibre for 1 kg/m^3 is 1.8 kg CO_2eq. Therefore, the dosage of synthetic fibre to replace steel fibres with same GWP potential will be obtained as follows:

Synthetic fibres dosage = $\frac{GWP\ of\ steel\ for\ given\ dosage}{GWP\ of\ 1kg\ of\ synthetic\ fibre} = \frac{26.4}{1.8}$ = 14.7 kg/m^3

Hence, a dosage of 14.7 kg/m^3 of synthetic fibres can be estimated as right dosage to obtain the required strength of 3 MPa for this case. Further testing of this dosage is required to finalise the dosage. Along with this, another important consideration could be to test synthetic fibres from different manufactures in order to see if a smaller dosage can be employed as a higher dosage of fibres could result in difficulties spraying shotcrete.

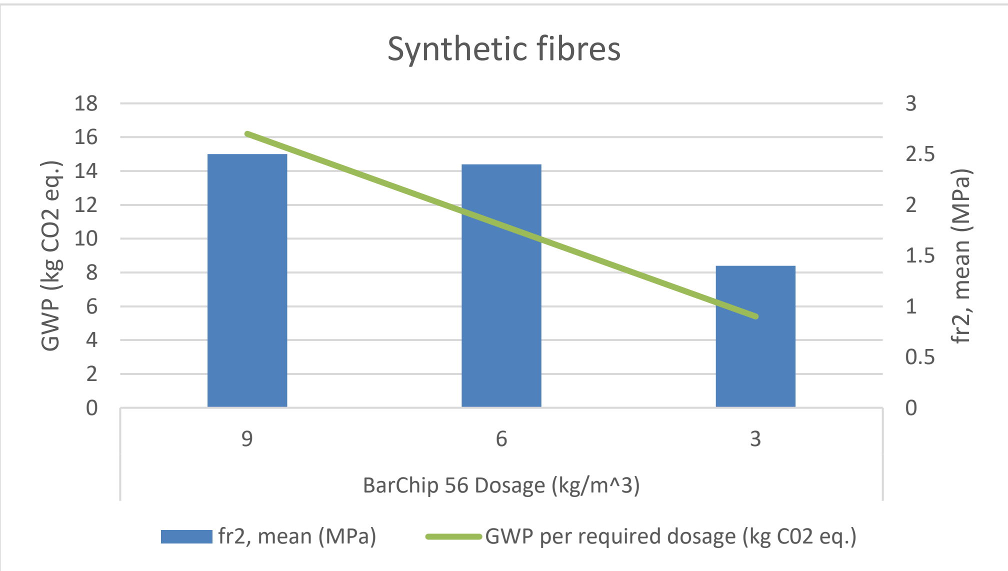

Figure 5.3: Results of flexural strength and GWP for synthetic fibres.

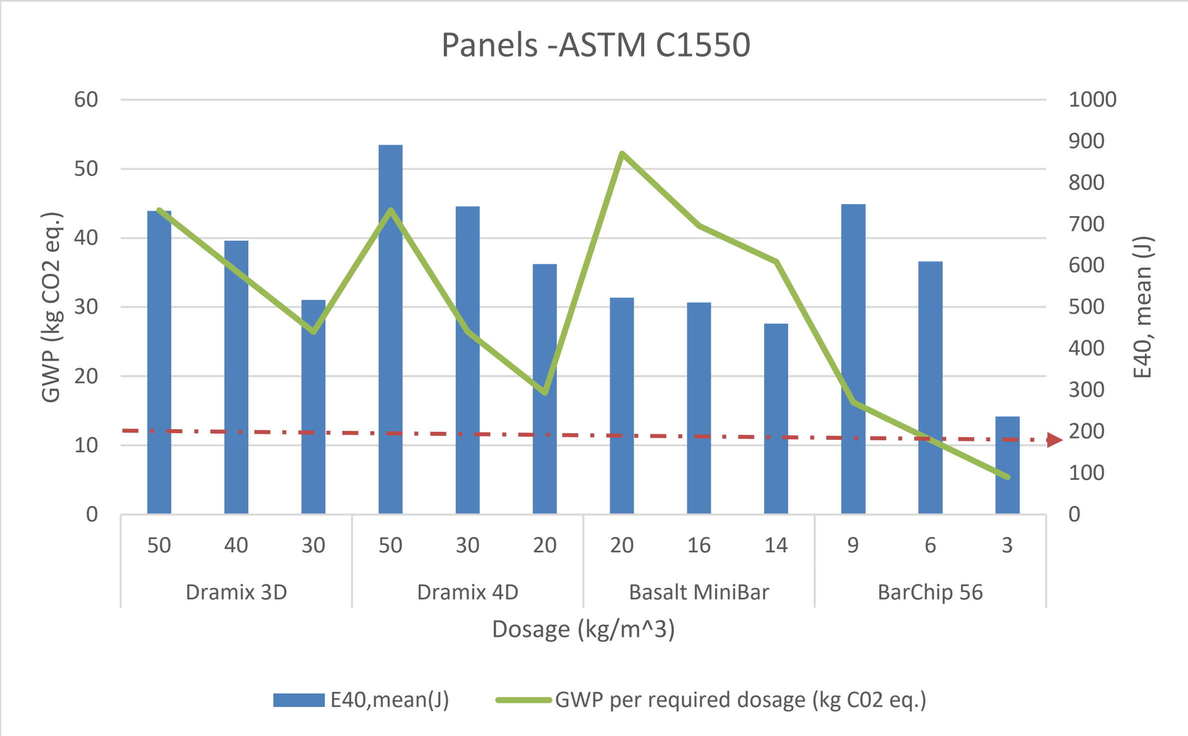

Figure5. 4: Results of energy absorption and GWP for all fibre types.

For the second case, concrete panels were cast as per the standards described in the codes with steel, basalt and synthetic fibres of different dosage. These panels were then tested according to ASTM C1550 (51) to find out the energy absorption at vertical deflection of 40 mm. For the current case study, the required energy absorption is 200 J which is achieved by every test batch for all fibre types, see Figure 5.4. It can be noted that for all dosages of steel and basalt fibres, the energy absorption is very much higher than the required energy absorption, hence a lesser dosage of fibres can be adopted. In case of synthetic fibres, 3 kg/m^3 dosage of fibre gives energy absorption a little over the required dosage, while other dosages have a much higher value. Hence for synthetic fibres, with respect to energy absorption, 3 kg/m^3 dosage of fibre could be an optimum choice. In case of steel fibres, for Dramix 3D, 30 kg/m^3 dosage of fibre gives the least value even though it is very much higher than the required value. And for Dramix 4D, 20 kg/m^3 dosage of fibre gives the least value even which is also still much higher than the required value. Hence a lower dosage of the fibre could be used to obtain the required energy absorption after they are being tested. For basalt fibres, even the lowest dosage which is 14 kg/m^3 gives very much higher than the required value of energy absorption and hence it would be feasible to use lesser dosage of fibres may be around 8-10 kg/m^3 after finalising by laboratory testing.

Since we know that synthetic fibres of dosage 3 kg/m^3can achieve required energy absorption and gives GWP of 5.4 kg CO_2eq. we can estimate the dosage of steel and basalt fibres based on this. Since 200 J is the energy required to be achieved, the dosage of steel and basalt can be estimated as following:

Dosage of steel fibres = $\frac{GWP\ of\ synthetic\ for\ given\ dosage}{GWP\ of\ 1\ kg\ of\ steel\ fibers}$ = $\frac{5.4}{0.88} = 6.1\ \text{kg}/m^3$

Dosage of basalt fibres = $\frac{GWP\ of\ synthetic\ for\ given\ dosage}{GWP\ of\ 1\ kg\ of\ basalt\ fibers}$ = $\frac{5.4}{2.61} = 2.1\ \text{kg}/m^3$

From this we see that in-order to achieve required energy absorption of 200 J, steel fibre of $6.1\ \text{kg}/m^3$ and basalt of dosage $2.1\ \text{kg}/m^3$ can be used achieving the same GWP as $3\ \text{kg}/m^3$synthetic fibres. However, these dosages are to be further tested in laboratories before application.

The calculations shown above can be summarised by saying that results from testing show that 3 kg/m^3 of synthetic fibres is sufficient to achieve the required energy absorption. Moreover, the lowest tested dosages of steel and basalt fibres resulted in energy absorptions much higher than the requirements. Therefore, a direct comparison between the studied fibre types is difficult since the dosage of steel and basalt can be reduced significantly. The maximum dosage of steel and basalt fibres that can be used to achieve the same GWP is calculated based on the GWP for 3 kg of synthetic fibres which is 5.4 kg CO2 eq. Hence, to achieve the same environmental impact as for synthetic fibres, the dosage of steel and basalt fibres can be calculated as the" Total GWP for synthetic fibres/ GWP per kilo of fibre". This yield that 6.1 kg/m^3 of steel fibres or 2.1 kg/m^3 of basalt fibres gives the same total GWP as 3 kg/m^3 of synthetic fibres.

Further discussing the other impacts presented in the results, we see that when steel, basalt and synthetic fibres are compared with respect to AP, we see that basalt has the highest value of AP. However, it is also important to note that the AP varies for different producers of the same fibre type. For example, steel fibre manufactured by ArcelorMittal has AP of 1.05 kg $SO2$ eq. whereas, steel from Mapei and Bekaert have 0.001 kg $SO2$ eq. and 0.004 kg $SO2$ eq. Overall, when fibres are compared with respect to the AP it can be seen that both steel and synthetic fibres have similar impact values. Synthetic fibres have compared to steel and basalt a smaller impact with respect to ODP. Basalt fibre and synthetic fibres form ADFIL show a lower EP value which indicates the impacts from production of these two fibres cause lesser emission of pollutants into water. These difference in values among different producers of same fibre type is dependant of the method adapted for various process used in production, source of energy used, transportation method employed. Hence it is very important to consider different factors in order to study the total impact caused by fibres.

Chapter 6

CONCLUSION

6.1 CONCLUSION

The work presented above was conducted with an objective to analyse fibre alternatives for shotcrete with regards to environmental impact and to suggest an optimum dosage of the fibre with respect to least GWP. Firstly, the working and design of tunnel support system using shotcrete and rock bolts were analysed. Second, individual fibres were studied in detail to understand their technical production process, application, advantages and disadvantages. All the steps and process involved from raw material extraction to finished fibres production were presented in form of flow charts. Later, in detail understanding of LCA and EPD according the standard codes were studied. EPD for fibres was obtained from producers of fibres to extract information regarding GWP. Further, the laboratory results obtained are compared for different fibres with respect to total GWP for different dosages of each fibre. The fibres are analysed based for two cases: residual flexural strength and energy absorption. Fibre with least dosage reaching the required values of strength and energy absorption with lower GWP value is present as optimum solution.

Based on the results in this thesis, synthetic fibres could be effective in obtaining the required strength and energy absorption with a lower GWP compared to other fibres if the dosage is slightly increased. However further testing of different dosage for different synthetic fibres should be carried out. It can be concluded that synthetic fibres are the best and optimum replacement as per the current study carried out. It is important to note that many other aspects such as maintenance, use phase and recycle stages of the fibres are not taken into account. It is important to consider the use phase and recycling phase of fibres in order to obtain a complete cradle to grave environmental assessment. Research to develop recycling methods for the waste produced from use of synthetic and basalt fibres in shotcrete has to be conducted. Along with this other impact categories reported in EPD are not being addressed and discussed. The results presented here are only based on GWP. However, other environmental categories also play prominent role in deciding a more environmentally friendly fibre alternative. In this case, testing was conducted with a limited number of specimens due to budget and time constraint. Testing of more specimens and with different dosage has to be carried out as it might result in less scatter of the results giving clear idea of the optimum dosage for each fibre type.

Hence, based on the results from the laboratory and the discussions above for this case study 14.7 kg/m^3 of synthetic fibre dosage is efficient in obtaining required flexural strength of 3 MPa and for the case of energy absorption 3 kg/m^3 dosage of synthetic fibre is sufficient with least GWP impact. The dosages presented here are strictly in regards to the GWP values only but for actual consideration in real scenario many other technical factors and environmental impacts have to also be taken into account before designing the dosage of fibres. But, with the present study conducted and results discussed, it is possible to say synthetic fibres can be the potential alternative than steel and basalt fibres in order to have shotcrete with better environment performance and lesser climatic impact with respect to GWP only being considered.

6.2 FUTURE SCOPE OF STUDY

The dosage of fibres should also be kept lesser to avoid problems while pumping of shotcrete. Due to constrain in availability of EPD and also the scope of study only a few manufacturers under each fibre type are considered. It will be further interesting to study fibres from different manufacturers as it can give different results. We know that steel fibres have deterioration due to corrosion which causes problem in the long run. Similarly, it is important to study and understand deterioration of basalt and synthetic fibres. It would also be very interesting to conduct entire life cycle assessment of shotcrete which could give a broader perspective regarding sustainability. It should be made compulsory for every manufacturer to conduct LCA of their products and make the EPD report available and accessible to everyone so a better alternative of building material can be chosen from environmental point of view.

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