Deliverable 1

Performance evaluation, material and specification development for basalt fiber reinforced polymer (BFRP) reinforcing bars embedded in concrete

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CHAPTER 1

BACKGROUND

This chapter provides a detailed description of Basalt Fiber Reinforced Polymer (BFRP) reinforcement bars (rebars) from the production of the fiber over the properties of the composition material of the rebar and its usage. Fibers and composite materials gained a lot of attention in the recent decades because of their wide availability and special properties like the high strength-to-weight-ratio. The first attempts to produce basalt fibers go back to Paul Dhé (from Paris, France), who invented a basalt fiber furnace in the United States in 1923 (Dhé, 1923; Colombo et al., 2012). The technology did not gain a lot of traction in the U.S. due to initial production difficulties and more profitable opportunities with glass fibers. After the manufacturing process for glass fibers was successfully industrialized in Toledo, Ohio, by Games Slayter in 1933 (Slayter, 1938), the major fiber producers in the U.S. abandoned basalt fiber research in favor of their main glass products (Faruk et al., 2017). However, extensive research on basalt fibers was conducted in the former Soviet Union, during the Cold War (Jamshaid and Mishra, 2016), for military purposes in a search for ballistic resistant textiles. After the Soviet Union collapse in 1991, the research projects were declassified (in 1995) and released for civilian applications. In consequence, basalt fibers are a recent development in the construction industry and most basalt fiber producing companies are now located in countries that used to be associated with the Eastern Bloc (Zych and Wojciech, 2012). Nowadays, basalt fibers gain attention from different industry fields all over the world. Before the fibers can be used for composite products the fiber itself is produced from raw basalt. Therefore, the next section 1.1 is introducing the origin of basalt fibers.

1.1 Igneous Rocks

The source material is an important factor in the characterization process for basalt fibers. Igneous rocks are one of the three main classes of rocks, besides sedimentary and metamorphic rocks. Igneous rocks are formed from melted rocks, mostly classified on the basis of their composition (either mineralogical or chemical) and according to their silica content. Molten rock material below the surface is called magma and turns into lava as soon as the surface is reached. Igneous rocks have to be separated into plutonic rocks on the one side (coarse-grained igneous rocks that solidified within the crust), which are usually classified according to their mineralogical composition and on the other side, volcanic lava rocks (fine-grained and solidified at or very near the earth crust surface with a faster cooling process), which are classified according to their chemical composition (Best, 2003).

Basalt is the most common volcanic rock on Earth and basaltic rocks (including gabbro, diabase, and their metamorphosed equivalents) are the most common rocks in the earth crust. Gabbro is a coarse-grained plutonic equivalent of basalt that solidified within the earth crust. Diabase is compositionally equivalent to gabbro and basalt but in its physical structure (grain structure) between them. It forms into basalt when it solidifies rapidly and to gabbro when more time is given for the crystals to grow (Maitre, 2002). Besides the structural differences the chemical structure is defined for all three types of raw basalt the same shown in Table 1.1. Basalt has a strict chemical definition that contains more than 45 and less than 52% of SiO_2 and

Table 1.1: Average chemical composition of basaltic rocks based on 3594 analyzed rock samples

Rock Type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Basalt	49.97	1.87	15.99	3.85	7.24	0.20	6.84	9.62	2.96	1.12	0.35

less than five percent of total alkalies (K_2O + Na_2O). High silica and low iron contents ensure the production of fibers with high strength properties. When meeting the requirements of the chemical composition, any of the described raw materials can be used for the basalt fiber production, which is regulated by different national documents. In this case, for the production of BFRP rebars, the Russian specifications for basalt fiber-reinforced polymer rebars as polymer composites reinforcement are defined as melted basalt or gabbro-diabase (ISC, 2014). After the clarification of the proper source for the fiber production the next section 1.2 shows the manufacturing process of fibers.

1.2 Fiber Types and Production

The section below summarizes the main fiber types that are in use for structural engineering applications. Additionally, the two production methods for basalt and glass fibers are explained to have a comparison to the most used fiber types.

Fibers commonly used to produce FRP rebars are glass, carbon, and aramid because of their higher tensile strength in comparison to traditional steel. As a drawback compared to steel, tensile failure of FRP rebars show a non-ductile failure of the fibers with sudden breakage. Basalt fibers show better mechanical properties than glass fibers they are more widely available and cheaper than carbon fibers (Zych and Wojciech, 2012). Continuous basalt fibers have become commercially available as an alternative to glass fibers. Glass has been the predominant fiber for many civil engineering applications because of an economical balance of cost and specific strength properties. In addition, they were better researched and used in the united states, but apparently, products from russia, china, and countries located in areas in and around the former soviet union are becoming available to the international market offering different kinds of fibers (ACI Committee 440, 2007). The following subsections detail the production of different fiber types, starting with basalt based fibers.

1.2.1 Basalt Fiber

According to the Russian specifications for fiber-reinforced polymer bars, basalt fibers for polymer composites reinforcement are made from melted basalt or gabbro-diabase (ISC, 2014) as described in Section 1.1. The schematic process of the basalt fiber production is shown in Figure 1.1. Starting on the left side of the figure, the raw basaltic rock is first crushed, washed, and then transported to a furnace. The melting process requires a minimum melting temperature of approximately at 1450°C (2640°F). Unlike glass, infrared energy is absorbed by the opaque basalt, and therefore, it is more difficult to uniformly heat the entire basalt mixture. Molten basalt must be held in the smelter for extended periods of time to ensure a homogeneous temperature. When melting occurs and uniformity is reached by removal of gases, the molten basalt flows
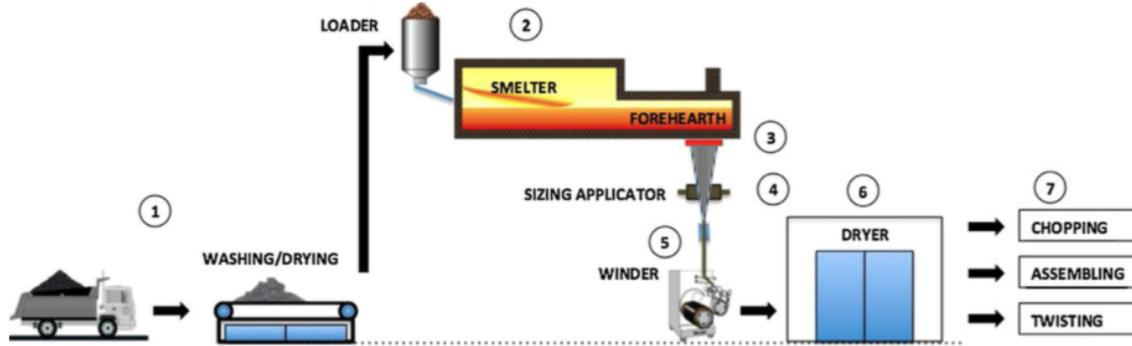
Figure 1.1: Continous basalt fiber production process (Ipbüker et al., 2014)

into the fore hearth (Ipbüker et al., 2014). The molten material is forced through a platinum/rhodium crucible bushing with 9 to 24 micrometer nozzles to extrude continuous fibers. Basalt fibers are sized during the manufacturing process (in exactly the same way as glass) to protect the fiber and to impart the resin compatibility needed for optimum performance. Sizing such as starch, gelatin, oil, or wax is applied to improve the bond and to minimize degradation of filament strength that would otherwise be caused by filament-to-filament abrasion (Bagherpour, 2012; Zych and Wojciech, 2012). The fibers are made in the form of chopped fibers (cheaper and lower mechanical properties) or continuous fibers rovings (spinneret method) (Fiore et al., 2015). After the basalt fibers are produced, they are converted into a suitable form for each particular application (Pavlovski et al., 2007).

Only raw basalt is necessary to produce the fibers, and the purity of the raw material for the fibers depends only on the rock source. As a consequence of specific kind of original rock sources, more than one category of basalt fibers with different chemical compositions may be obtained. Due to these factors, basalt fibers may take on different mechanical or physical properties (Zych and Wojciech, 2012). During the production process no additional components are needed to produce basalt fibers. Toxic ingredients can be omitted, therefore, they are considered as a "greener product" (relative to glass fibers) (Zych and Wojciech, 2012). While the production of glass fibers requires the addition of several ingredients, and a tedious mixing process of those. The properties and production process is listed in the upcoming subsection 1.2.2.

1.2.2 Glass Fiber

This subsection describes glass fibers and their production. The most common types of glass fibers are electrical (E-glass), high strength (S-glass), and alkali-resistance (AR-glass). E-glass is the most common reinforcement material used in civil and industrial structures. Those fibers are named E-Glass because they offer high electrical insulating properties. In addition, the are known for low susceptibility to moisture, and high mechanical strength. It is produced from lime-alumina-borosilicate, which can be easily obtained from an abundance of raw materials like sand (Bagherpour, 2012). S-glass provides higher tensile strength and modulus of elasticity but is more cost prohibitive and less preferable than E-glass. AR-glass is very resistant in high alkali environments such as in concrete, but at the moment, no compatible sizing is available to use it in the FRP production where the fibers are combined with a thermoset resin (Nanni et al., 2014).

The main difference to basalt fibers is that glass are made from a complex batch of materials, whereas

basalt filament is made from melting basalt rock with no other additives, which reduces the environmental impact. Major ingredients of the batch of materials are silica sand, lime stone, and soda ash. Silica sand is the glass former, while lime stone and soda ash is added for lowering the melting temperature. Additional materials can be mixed in for manipulating certain properties like adding borax for more chemical resistance (Aubourg et al., 1991). Fiberglass furnaces are generally divided into three distinct sections. First, the batch is delivered into the furnace section for melting. Then, the molten glass flows into the refiner section, where the temperature of the glass is lowered from 1370°C (2500°F) to about 1260°C (2300°F). In the last step, the molten glass os transfered into the end section located directly above the fiber-forming stations. The molten mass is rapidly cooled to prevent crystallization and formed into glass fibers by a process also known as fiberization. Nearly all continuous glass fibers are made by a direct draw process and formed by extruding molten glass through a platinum alloy bushing that may contain up to several thousand individual orifices (Wallenberger et al., 2001). Typical glass fiber diameters range from 3 to 20 micrometers. Individual filaments are combined into multifilament strands, which are pulled by mechanical winders at velocities of up to 61 m/s (200 ft/s) and wound onto tubes or forming packages (Wallenberger et al., 2001). After describing the production of glass fibers, carbon fibers are presented in the next subsection.

1.2.3   Carbon Fiber

Primarily, carbon fibers are used for pre-stressed strands (and not as much for regular rebar purposes) in civil structures because of their high tensile strength, high modulus of elasticity, and most importantly, because of its creep resistance, which is significantly higher when compared to glass or basalt fibers. Carbon fiber composites are fibers made from polyacrylonitrile (PAN) classified as high-modulus carbon fiber. Fibers made from carbon typically have a high fatigue strength, high resistance to alkali or acid attacks, a low coefficient of thermal expansion (CTE), and high electrical conductivity. However, it also has a relatively low impact resistance, can cause galvanic corrosion in contact with metals, and has a significantly higher unit cost. Accordingly, proper sizing must be applied before these fibers can be embedded in resin similar to other fibers on the market. Moreover, carbon fibers are the ones with the highest tensile strength (three times the strength of glass fibers) , but they are also the most expensive ones (about ten times more than glass fibers) (Nanni et al., 2014). Another fiber type used for engineering purposes are aramid fibers (see subsection 1.2.4).

1.2.4   Aramid Fiber

Aramid fibers are organic aromatic polyamide based with high fatigue and creep resistance. In addition, these fibers are a good isolators for electricity or heat. However, they are sensitive to ultraviolet (UV) light, high temperature, high humidity, and a chemical or mechanical bond between the aramid fibers and resin is difficult to achieve (Bagherpour, 2012). Within the wide availability of different grades, Kevlar 29, 49, and 149 are the most common fibers in structural applications. Compared to glass fibers, aramid fibers have a higher tensile strength and also a 50 % higher modulus of elasticity. Nevertheless, the use of these fibers is limited by the high material costs in the production of FRP bars (Nanni et al., 2014).

1.2.4.1 Fiber Types Summary

To summarize the available fibers Table 1.2 lists typical mechanical properties of those fiber types (Nanni et al., 2014). The table contains average densities, tensile strengths, tensile modulus and ultimate tensile

Table 1.2: Typical properties of fibers (single filament)

Type of Fiber	Density[†]		Tensile strength[‡]		Tensile modulus[‡]		Ultimate tensile strain
Basalt	4720	2800	700	4827	12.9	89.0	3.1
E-glass	4215	2450	500	3448	10.5	72.4	2.4
E-CR glass	4416	2620	508	3500	10.5	81.0	
S-glass	4215	2450	660	4550	12.4	85.5	3.3
AR-glass	3800	2250	$260-500$	$1793-3448$	$10.1-11.0$	$69.6-75.9$	$2.0-3.0$
High-modulus carbon	3290	1950	$360-580$	$2482-4000$	$50.7-94.3$	$349.5-650.2$	0.5
Low-modulus carbon	2950	1750	507	3496	34.8	239.9	1.1
Aramid (Kevlar 29)	2428	1440	400	2758	9.0	62.1	4.4
Aramid (Kevlar 49)	2428	1440	525	3620	18.0	124.1	2.2
Aramid (Kevlar 149)	2428	1440	500	3448	25.4	175.1	1.4

[†] $1\,\text{lbs./yd}^3 = 0.593\,\text{kg/m}^3$

[‡] $1\,\text{ksi} = 6.895\,\text{MPa}$

strains of different fiber types, which are described in the subsections above. Compared to the other fibers basalt has the highest density and the second highest ultimate strain. Just aramid (Kevlar 29) has a higher strain. The lowest strain combined with the highest tensile modulus can be seen at carbon fibers (Low- and high-modulus). Glass fibers are showing the the lowest tensile strength and modulus. Aramid fibers, in addition to carbon fibers, are not suitable for the commercial use of composite rebars, because of economical aspects. Therefore, the focus for FRP rebars is on glass and basalt fibers because of a wide availability and cost efficiency. While the most important fiber types are shown in the subsections above, the the next section 1.2.5 focuses on the properties of basalt and its comparison to glass fibers.

1.2.5 Properties of Basalt Fibers

The paragraph below is summarizing properties with their advantages and disadvantages of basalt fibers. Basalt is a volcanic rock that can be formed into continuous fibers through melting pure raw basalt and using technologies similar to the ones used for the production of glass fibers. Due to the inherent properties of basalt, the fibers are more chemically resistant, have a higher tensile strength, and a modulus of elasticity that exceeds the elasticity of glass fibers by about 15 % to 30 % (Rarnalaishnan and Tolmare, 1998). In addition, basalt fibers are more UV-resistant, have a higher fire resistance, and they better maintain their physical characteristics in cold temperatures. Basalt fibers are reported to withstand temperatures from $-260\,°\text{C}$ to $750\,°\text{C}$ (Bagherpour, 2012). The variety of advantages is combined in a stiff rod used as reinforcement by adding a resin matrix. The composite system of fibers and resin is combining advantages of two materials to eliminated disadvantages of the individual parts. Therefore, the following section 1.3 details the different

resin types, their individual properties, and how the resin is used in the FRP rebar production.

1.3   Resin Types and Properties

Next to the fibers, the resin is the other important material to produce a proper FRP rebar. It is used to embed the fibers for a two-component system. The main functions of the resin matrix are to protect the fibers from mechanical and environmental attacks, to maintain the alignment of fibers, and to guarantee proper load transfer between individual fibers. Resins have proven their suitability for use in FRP reinforcing bars by maintaining chemical stability under harsh environmental conditions and by protecting the fibers from aggressive chemicals that would damage the filaments otherwise (Benmokrane et al., 2002).

Two major groups of resins exists: the thermoset (once cured, they cannot be converted back to their liquid state) and thermoplastic (soft when heated) resins. Thermoplastic resins are not usable for civil engineering purposes because they melt when heated and solidify when cooled. Thermoset resins cure permanently and irreversibly at elevated temperatures (Bagherpour, 2012). The most common thermosetting resins used in the composites industry are epoxies, unsaturated polyesters, and vinyl esters (ACI Committee 440, 2007). However, vinyl esters are predominately used for the production of FRP rebars followed by epoxy, but polyesters are typically excluded due to durability concerns. Initially, in their virgin state, thermoset polymeric resins are usually liquid at room temperature or solid with a low melting point as shown in Figure 1.2. The figure shows an example of a thermoset polymeric resin which is liquid at room

Figure 1.2: Thermoset polymeric resin used in FRP rebars

temperature, poured into a vessel. It can be used in the FRP rebar production process in a heated resin bath. Heat treatment and catalysts (hardeners) are used in the curing process, to solidify the resin. After the curing process is completed, the material is permanently solidified through polymerization/cross linking of polymer chains, as it cannot be converted back to its initial liquid stage. The properties of typical resin matrices for FRP composites are listed in Table 1.3. Vinyl ester has the highest tensile strength compared to epoxy and polyester, therefore, polyester has the lowest moisture content and epoxy resin has the highest glass transition temperature. The density, the Poisson's ratio (transverse strain to axial strain), and the Coefficient of linear thermal expansion (CTE) are similar for all three types.

The following subsections describing suitable resins for a FRP production, starting with subsection 1.3.1

Table 1.3: Typical properties of resin matrices

Type of resin matrix	Density (lb/yd^2)	Tensile strength (ksi)	Longitudinal modulus (ksi)	Poissons's ratio	CTE $10^{-6}/°F$	Moisture content (%)	Glass transition temperature °F
Epoxy	2000−2400	5−15	300−500	0.35−0.39	1.6−3.0	0.15−0.60	203−347
Polyester	2000−2400	7−19	400−600	0.38−0.40	1.3−1.9	0.08−0.15	158−212
Vinyl ester	1900−2300	10−11	435−500	0.36−0.39	1.5−2.2	0.14−0.30	158−329

$Notes: 1lb/yd^3 = 0.593kg/m^3; 1ksi = 6.89N/mm^2; °F = (9/5 * °C + 32)$

describing the specific properties of epoxy resin.

1.3.1 Epoxy

Epoxies are well-established in the civil engineering sector because of their lower shrinkage properties in direct comparison to vinyl ester. Epoxy resins are usually used for high-performance composites with superior mechanical properties, resistance to corrosive liquids and environments, superior electrical properties, good performance at elevated temperatures, and excellent adhesion to a substrate. However, they have a low ultraviolet (UV) resistance and requires post-cure (longer time in the die under certain temperatures) because of a higher viscosity than other resins (polyester or vinyl ester) (ACI Committee 440, 2007). Although epoxies can be more expensive than other resins, they are more suitable for high performance applications. Epoxy resins are compatible with most composite manufacturing processes and is also, at the moment, the predominant adhesive of choice for concrete repair with FRP products. (Bagherpour et al., 2009). The following subsection 1.3.2 provides necessary information about polyester resin.

1.3.2 Polyester

Polyester can be classified as saturated and unsaturated. Thermoset unsaturated polyester resins represent approximately 75 % of the composites industry. To initiate curing, the resin is dissolved in a monomer (like styrene) solution, so that it can react with the unsaturated ends on the polymer, which then converts to a solid thermoset structure. The advantage is the balance of properties, which include dimensional stability, cost efficiency, and ease of handling during processing. Because of different required properties such as flexibility, electrical insulation, corrosion, or heat resistance, a wide range of specific performance polyester resins are available (ACI Committee 440, 2007; Bagherpour et al., 2009). The last resin type combines advantages of epoxy and polyester, which are listed in subsection 1.3.3.

1.3.3 Vinylester

Vinyl esters were developed to combine the properties of epoxy resins with the fast curing of polyester resins. In fact, it has higher physical performance and costs less than epoxies. Due to the combined properties, mechanical toughness, and high corrosion resistance are obtained (ACI Committee 440, 2007).

Those ability enhancements do not need a complex processing or a special fabricating process like epoxy resins. Vinyl ester resins are most commonly coupled with glass fibers (Nanni et al., 2014). However, the current market BFRP rebars is combining basalt fibers is a with epoxy resin.

Consequently, the next section 1.4 provides common production methods for BFRP rebars, combining the fibers with the resin in an automated process for mass production.

1.4 BFRP Rebar Production

Different processes have been developed to combine the fibers and the resin for the efficient production of fiber-reinforced polymer rebars. Typical production methods for fiber reinforced composite materials are pultrusion, wet-laying, braiding, or weaving. According to the literature and manufacturers, production processes like braiding or weaving are not used for the FRP rebar production. The following section describes the currently common processes to produce basalt FRP rebars: pultrusion and wet lay-up process. Based on cost efficiency, production speed and product quality, pultursion is the dominant manufacturing method. However, the production method is not standardized, which may lead to different rebar products from one manufacturer to another, such that each rebar manufacturer may produce entirely different rebars. Different investigations were obtained to verify these processes and to identify possible weaknesses and to make recommendations for standardization requirements. Scanning electron microscope (SEM) analysis has shown that porosity and voids are present with BFRP rebars. Researchers recommend that improvement in the manufacturing process should be implemented to reduce and/or eliminate these defects (ElSafty et al., 2014). The first process is described in Subsection 1.4.1.

1.4.1 Pultrusion

The pultrusion method is the dominant process to manufacture FRP rebars because of its cost efficient and fast production. A continuous molding process combines fiber reinforcement and thermosetting resin, which produces a constant cross-sectional rebar (Figure 1.3). The figure shows from the left side on, that
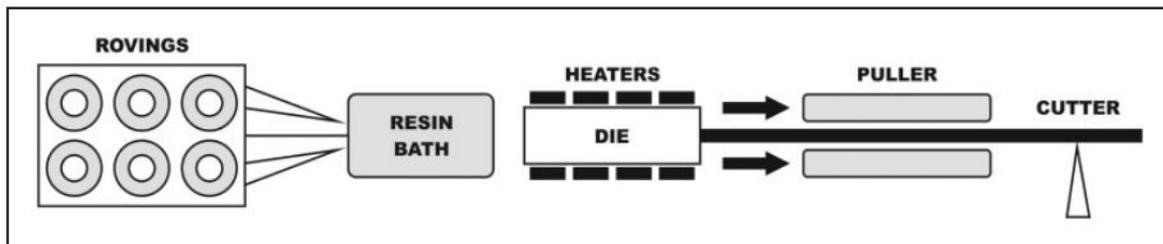
Figure 1.3: Schematic diagram of FRP rebar pultrusion (Borges et al., 2015)

fibers are continuously pulled from rovings, to be wetted (impregnated) with the desired liquid resin in a resin bath. Borges et al. (2015), investigated the influence of resin bath temperature on the properties of pultruted GFRP rebars with polyester resin. It was shown that temperatures between 30 °C to 50 °C were suitable for the production process. Higher temperatures lead to a low viscosity and an unproper wetting of the fibers before entering the heating die. The fibers are pulled through a heated metal die (with different heating zones) of the desired diameter, which defines the final shape. The recommended curing temperatures

for resins is about 177°C (Joshi et al., 2003). In the study of Borges et al. (2015) four heating zones were calculated ranging from 90 °C to 110 °C to 130 °C back to 110 °C again. The die was 900 mm long and the pulls speed was set at 0.46 m/min. Inside the pultrusion die, a controlled temperature lets the fibers and the resin harden while the heat activates the curing or polymerization of the thermoset resin until it changes its condition from liquid to solid. Inside the heating die the rebar reacts chemically and solidifies under an exothermic reaction forming from a liquid stage to a gel stage until the solid stage is reached. To set the rate of the manufacturing process, the gel time and the peak exothermic temperature of the thermoset resin need to be evaluated. The gel time is the moment where the mixed components start to solidify and the peak exothermic temperature is the maximum temperature the rebar itself reaches due to the reacting and therefore, appoint the time of the maximum reaction. Figure 1.4 is showing a sketch how the gel time and the position of the exothermic peak is evaluated (according to ASTM D 2471 - "Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting of Thermosetting Resins"). After
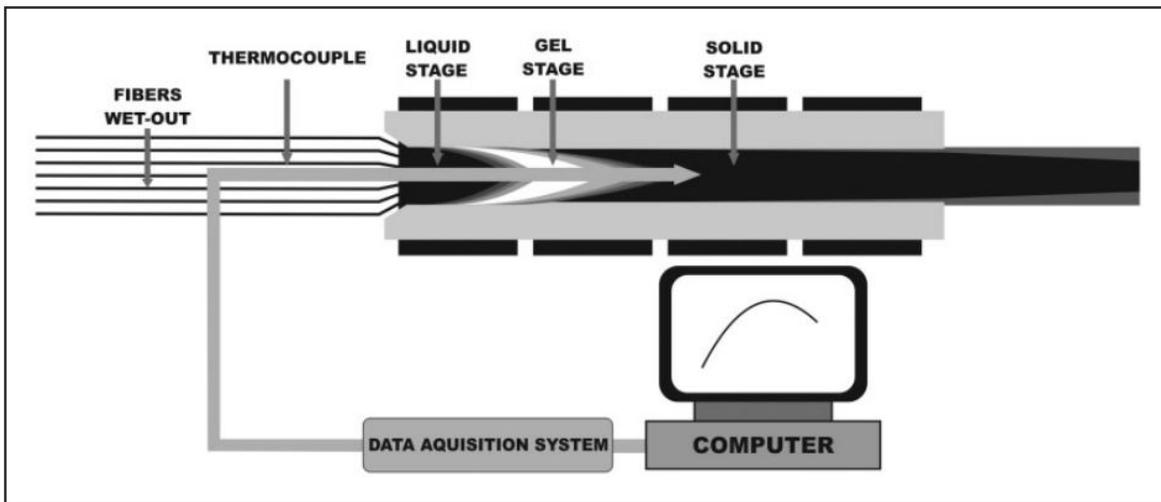

Figure 1.4: Obtain position of exothermic peak (Borges et al., 2015)

the wet-out on the left side of the figure the bundled fibers enter the heating die. A data acquisition system is collecting the data of the different hardening stages of the fibers to measure the exact point of the solid stage to determine the curing time in the die. Internal defects in the cured material, which can lead to lower durability and mechanical properties can be caused by estimating an incorrect rate. Therefore, the production rate is determined by the curing time of the resin. The composite solidifies when cooled and is cut to the desired length after pulling it through the pultrusion machine. Different processing variables can affect the quality and process efficiency like: die temperature, fiber content, pull speed, cure time, or resin viscosity. Accordingly, product availability and company logistics are constrained only by storage and transporting limitations. The pultrusion process has a significant influence on the final properties of FRP rebars, as it affects the rate of resin polymerization, the air void content, and thus, the fiber content. Moreover, to achieve a sufficient bond between concrete and and the produced rebar in its final application, an additional process is required to apply the so called surface enhancement features. (You et al., 2015). This can come in the form of ribs, sand coating, or helical wrap. Because of the fixed cross section of dies, a tight dimensional control of FRP rebars is assured. The pultrusion is considered to be a relatively simple process for the manufacture of FRP bars, particularly for the production of straight rods. Coiling is also possible when smaller diameters are produced (ACI Committee 440, 2007; Patnaik, 2009). Because of

limitations of the method small diameters are also produced with the production process explained below (see Subsection 1.4.2)

1.4.2   Wet Lay-Up

A newer FRP rebar production process is the wet lay-up process, developed by a Norwegian company (ReforceTech AS Norway). Because it is a recent development in the production of FRP rebars, products manufactured with this technique have not been researched widely. The production costs are believed to be reduced in comparison to the traditional pultrusion method because of a simple process with reduced working staff.

Wet lay-up is used to produce simple composites, shown schematically in Figure 1.5. A programmable
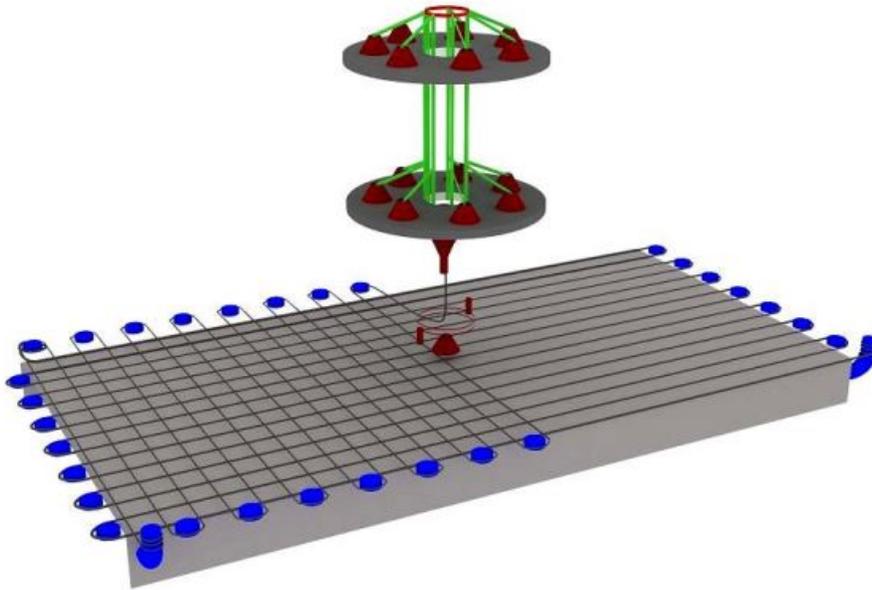
Figure 1.5: Wet lay up process scheme (Banibayat, 2011)

arm with controlled movement in three orthogonal directions manufactures the rebars with the desired length and shape. Fibers impregnated with a polymeric resin are automatically laid to form a FRP rebar after curing. The fibers are guided through a funnel-like resin bath where thorough wetting and impregnation of the fiber take place. The wet fiber is then pulled to a working platform. Several layers are laid up one over the other to produce a one-dimensional FRP construct. This new production method is said to be cheaper but contains several disadvantages such as inconsistent cross-sectional shapes or uneven surfaces due to non-uniform pull on the fiber threads, which leads to a wavy surface. However, this waviness attribute can be beneficial for bond to concrete behaviors but also leads to lower tensile strength. Bar diameters of 0.2 in. (5 mm) to 0.6 in. (16 mm) were successfully produced using this process (Banibayat, 2011).

After the production process, tests of physical, mechanical and durability properties are necessary for quality control and product verification processes. Mechanical testing is important for the specification and certification of FRP rebars. Therefore, the test procedures are described in Section 1.6, with a special focus

on the tensile properties in Subsection 1.6.2.1, because they are the most important characteristic for the rebar classification and in engineering design. Hence, the next section provides a general overview of the most important characteristics, before detailing each test procedure individually.

1.5   BFRP Rebar Properties

This section focuses on the properties of the produced FRP rebar. These material characteristics of the final product are important for the application in civil structures. Figure 1.6 summarizes the process for the production of basalt fiber reinforced polymer (BFRP) reinforcing bars (rebar). Basalt fibers manufactured
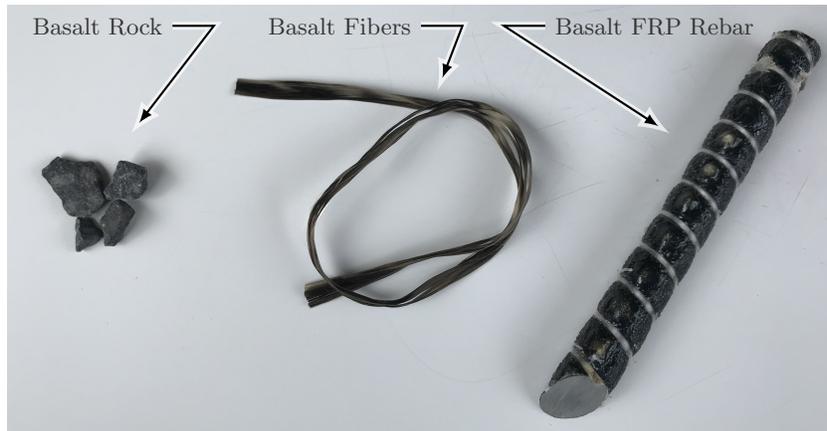

Figure 1.6: Basalt FRP rebar production steps

from molten basaltic rocks are embedded in a polymeric resin matrix, similar to GFRP rebars (from left to right). Mainly, fibers are known for their high tensile strength-to-weight ratio and — specifically when they form rebars — for corrosion resistance, as compared to black steel reinforcement. The fiber volume is mainly responsible for the tensile strength of the FRP rebar. According to the ASTM D 2584 "Standard Test Method for Ignition Loss of Cured Reinforced Resins" the fiber content shall not be less than 55 % by volume or 70 % by mass and shall be reported by volume or by mass in accordance with the method used (ASTM-International, 2011). However, a volume fraction of about 80% is common for FRP rebars, and according to Bagherpour et al. (2009), a fiber content beyond that does not allow the fibers to be completely surrounded by the resin matrix. The tensile behavior of FRP rebars is characterized by a linear elastic stress-strain relationship up to failure as shown in Figure 1.7. The graph shows the stress-strain diagrams for different FRP composites compared to the stress-strain curve for steel (dot-dash line). The y-axis are shows the tensile stress in MPa on the left and in ksi on the right side. The tensile strain in percent is provided on the x-axis. It can be seen that the incline of the FRP products are smaller than the one of steel (lower E-Modulus) but the point of maximum tensile stress is significantly higher for all FRP products. The biggest incline and highest tensile stress with the lowest strain is reached by carbon FRP (tightly dotted line) followed by aramid FRP (dash line) which has a higher strain than basalt FRP (straight line). Glass FRP (wide dotted line) can be pointed out as the FPR product with the lowest tensile stress and lowest elastic modulus and basalt FRP is situated between aramid and glass. Compared to steel rebars, basalt FRP rebars offer higher tensile strength but lower ultimate tensile strain and lower tensile modulus of elasticity, which results in a more brittle failure for FRP products. Unlike steel, the tensile strength of a FRP rebar varies
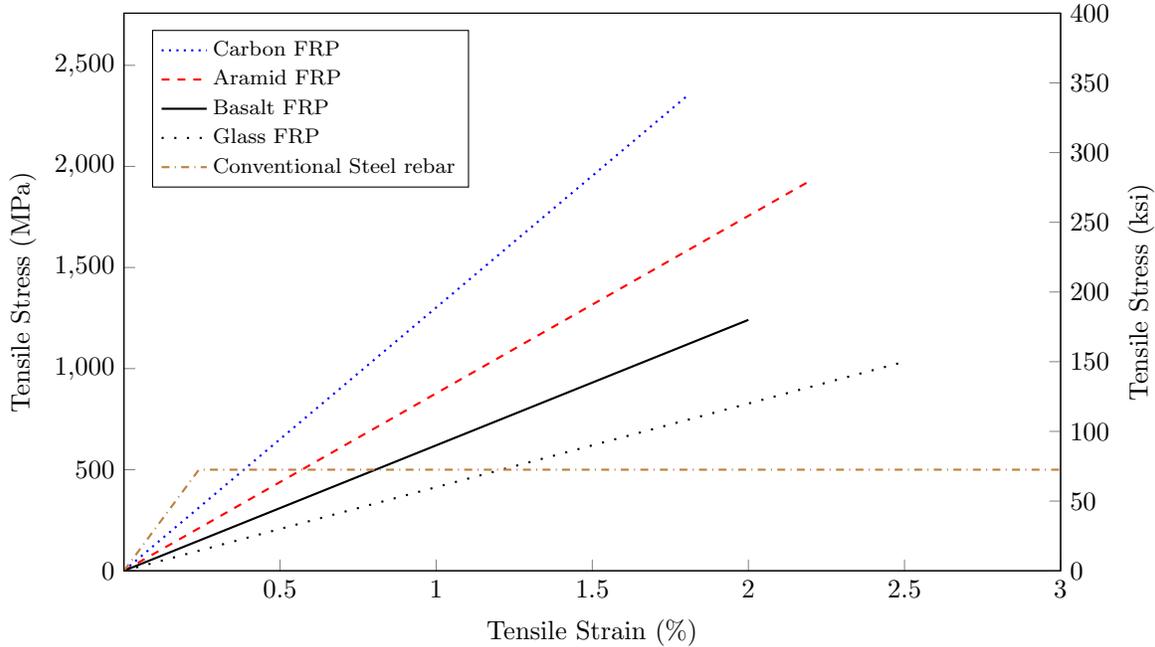
Figure 1.7: Tensile stress and strain of different types of fibers according to Busel (2016)

with its diameter, while the longitudinal modulus does not change appreciably. Based on the ongoing FDOT research project BDV 30 TWO 977-18, it is assumed that this phenomenon (known as shear lag) is due to the fact that the tensile force is usually introduced at the outer surface (via anchors) and the outer fibers have to transfer the load to the adjacent (inner) fibers through shear stresses in the resin matrix. Therefore, the shear lag effect becomes more significant as the bar diameter increases because the core of the bar is further distanced from the outer surface and more resin must be activated. This leads to lower strength measurements for larger diameter rebars because the inner core may not contribute to the load carrying mechanism before the outer most fibers start to fail. The tensile strain (or stretch) in the outermost fiber reaches its limit before the innermost fibers start to deform. The reason for the longitudinal modulus to remain almost constant (while the strength reduces with increasing bar diameter) is assumed to be a result of the measurement technique, in which an extensometer is applied at the outermost surface — at the fiber that is activated to its full potential — independent of the rebar diameter.

1.6   Test Procedures for FRP Rebar

To use any new FRP rebar product in publicly funded infrastructure projects, it has to meet or exceed specific test criteria and must be certified by a FDOT approved laboratory. Numerous properties, such as the cross-sectional area, fiber content, moisture absorption, tensile strength, horizontal and transverse shear strength, bond strength, durability, etc. have to be evaluated for test groups that include multiple specimens from different production lots. The following subsections detail these tests to provide a overview of the general acceptance process and to provide context for the associated acceptance criteria listed in the next Chapter.

1.6.1 Physical Characteristics

1.6.1.1 Density and Cross-Sectional Area

To monitor physical changes in a sample while testing, and to indicate degree of uniformity in different specimens, the specific gravity of the product is determined through multiple specimens. A clean specimen is conditioned for at least 40 h prior to testing in a temperature range from 21 °C to 25 °C at a moisture content between 40 % and 60 %, then it is cut to the desired length (while the minimum length is 10 mm and the maximum length is 50 mm) and the weight is recorded to the nearest 0.05 g. The recorded weight of the curtailed specimen should measure a minimum of 5 g and a maximum of 50 g. The density of test specimen is determined via the principle of buoyancy and the cross-sectional dimensions are calculated by dividing the determined volume by the measured specimen length. For the calculation of FRP rebar strength properties, the measured cross-sectional area is an important characteristic because strength values can differ significantly between strength values determined via nominal diameter dimensions and values determined from the experimentally measured area. It is the cross-sectional area per ASTM D 792 (ASTM-International, 2015b) that is used in many of the following test procedures to determine the strength characteristics.

1.6.1.2 Fiber Content

To obtain the loss of resin in cured reinforced sample when exposed to constant high temperature, and to study the structure of the composite material via the relative material proportions (percentage of fibers vs. percentage of resin by weight), the FRP rebar specimens are tested for fiber content. A clean specimen is first conditioned for at least 40 hours prior to testing in temperature range from 21 °C to 25 °C at moisture content between 40 % and 60 %. Three samples (at minimum) with a known weight of at least 5 g and a maximum size of 25 mm × 25 mm in a crucible (of known mass) are exposed to a minimum of 565 °C in a muffle furnace until all resin is burnt and only the fibers remain. If the rebar product was made with sand on the surface for bond enhancement, this sand must be removed from the crucible before determining the fiber content. The percentage of fibers can be determined through the difference in weight before and after the burning process.

1.6.1.3 Absorption

The moisture absorption properties of FRP rebars are determined according to ASTM D 5229 test standards. A total of 7 different methods are provided in ASTM D 5229 to find the moisture absorption in different environments. Procedure A is most commonly used, and is therefore, followed and described for this research project as well. At least three specimens per bar type are oven dried, if any moisture is present. Three diameter measurements are taken at 120° intervals perpendicular to the longitudinal axis of the FRP rebar, and those measurements are recorded to the nearest 0.001 mm. Then, each specimen is weighted with a precision of 0.05 g in its dry state. The specimens are then submerged in distilled water at a constant temperature. After two weeks in the water bath, the specimens are removed and the surface is toweled dry so that no free water remains on the surface of the rebar. weight measurements are taken again with a precision of 0.05 g. This procedure is repeated and weight gains are monitored until three consecutive two-week measurement do not differ significantly from one another.

1.6.2 Strength Characteristics

1.6.2.1 Tensile Properties

The test procedure to measure the tensile strength of FRP rebars is described in the ASTM D 7205/ D 7205M-06 (ASTM-International, 2015a). Because of the low shear strength of the FRP rebar, special preparations are required to properly test the rebars and to obtain proper results. A naked FRP rebar, griped by the testing machine would fail under high transverse stresses at the grip during the pulling process without reaching the ultimate tensile strength. Therefore, ASTM D 7205 describes a method in which the FRP rebar has to be anchored on both ends with a steelpipe that is filled with an expansive grout or resin to transfer the loads from the testing machine into the rebar through friction. The grout or epoxy inside the anchor forms a cylindrical shell around the specimen. Because of the high stiffness of the steel tubes, the grout or epoxy exerts pressure on the specimen, which decreases the risk of premature failing in the grip region and clamps the rebar inside the steel tube. The basic idea of this system was to provide lateral pressure on the rebar in a sleeve to prevent slippage of the rebar. Further research work has shown that an internal pressure between 25 MPa (3.6 ksi) and 70 MPa (10 ksi) generated by the expansive cementitious material in the sleeve is enough to grip FRP tendons with different surface treatments (Schesser et al., 2014). The rebar with two anchors on the ends is then installed (after the grout cured one week) into the testing machine or into a fixture which is mounted into a test frame. Figure 1.8 illustrates one end of the prepared FRP sample with the applied anchor system. Normally, such grouts are poured into holes drilled in rock or concrete as
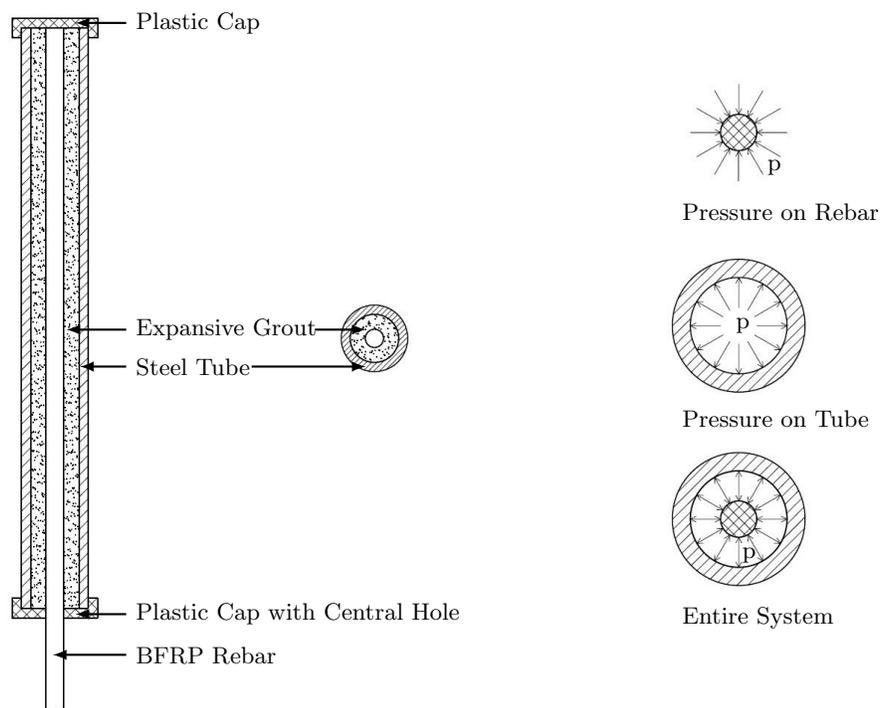

Figure 1.8: Tensile strength test load transfer (Schesser et al., 2014)

a non-explosive demolition agent. Because larger diameter rebars fail under higher loads, a longer anchor length (more friction) is required for longer rebars. The rebar diameter dependent anchor length is listed in

ASTM for each rebar size.

According to the ASTM, the specimen length is dependent on the tested diameter of the rebar. The total specimen length consists of two anchors of the both ends of the FRP rebar and the free specimen length in between the anchors. Because of shear lag effects, ASTM D 7205 prescribes the free specimen length with 40 times the diameter. Besides the effect of the gripped part of the FRP rebar test specimen, the free specimen length has not been fully evaluated yet, and only a few researchers have studied the behavior on GFRP rebars. The study of Castro and Carino (1998) dealt with tensile tests on five different GFRP rebar types (Diameter 9 mm to 15 mm) with a free specimen length from 40 to 70 times the diameter. The anchor lengths was set with 15 times the rebar diameter, which was evaluated in an expeditious approach and found to be the minimum anchorage length to avoid slippage of the FRP rebar. The intention was to evaluate the influence of the free-length-to-bar-diameter ratio on the measured tensile strength. The tested specimen from different manufacturers and different rebar diameters lead to no significant influences on the results. Different than Castro and Carino (1998) approach of longer specimen, the project of Gieben (2017) evaluated tensile tests on GFRP rebars from different sizes and manufacturers with a smaller free specimen length from 20 to 40 times the diameter. Three tensile tests per manufacturer (three in total) were occurred. Tests showed no significant impacts on the final results compared to mechanical results according the ASTM D 7205 regardless of the free specimen length. Additionally according to (Gieben, 2017), the elastic modulus, calculated from the standard range between 0.1% and 0.3%, should be calculated between 0.2% and 0.3% for short specimens with a free length of 20 times the rebar diameter. The tensile tests of the short specimen length illustrated a non-linear behavior under reduced loads (low strain range). Instead, all specimens in this research, independent of the free specimen length, measured identical elastic moduli (within each test group) in the higher strain ranges. However, it should be noted that the free test length (between the grips of the test machine) of traditional steel reinforcement bars is merely 15 times the bar diameter (Neroth. and Vollenschaar, 2011).

Aside from the dimensions, ASTM D 7205/ D 7205M-06 ASTM-International (2015a) also prescribes the procedure for determining the elastic modulus of the rebars. The tensile modulus of elasticity should be calculated from the strain range of the lower half of the stress-strain curve, with the starting point at a strain of 0.1 % and the end point at a strain of 0.3 %. Therefore, the elastic modulus is calculated from deformation measurements at relatively low stress levels. Strain measurements are obtained on the outer fiber of the rebar with an extensometer. The shear lag effect is not considered in this method, underlined by constant values for the modulus of elasticity (Gieben, 2017).

The tensile strength, however, is determined from the ultimate load divided by the cross-sectional area. As a consequence, the test results of the elastic modulus are generally showing a low variance, while the ultimate stress differs widely from one specimen to another. This is because structural effects like local air voids and residual stresses are affecting the tensile properties, while these factors do not have an influence on the material behavior under low stress and thus no influence on the elastic modulus. The ultimate stress, in turn, is not only determined by the properties of the raw materials, but also by their interaction with each other (Ehrenstein, 2006).

These interactions allow the rebar to develop additional properties, which make the product suitable for a use as reinforcement in concrete dealing with harsh environments. Accordingly, the properties of the combined materials as a reinforcement bar are described in section 1.5 below.

1.6.2.2 Transverse Shear Strength

The transverse shear strength is an important characteristic if the bars are used as dowels in concrete pavement, stirrups in concrete beams, or as general shear reinforcement elements. ASTM D 7617 (ASTM-International, 2012b) is used in the process of testing and analyzing the data. Before testing, the specimens are conditioned according to the ASTM D 5229 (ASTM-International, 2014). The conditioned specimen are then cut to length with a minimum length of 225 mm so that they fit in the shear fixture which is a device that produces double shear on the FRP rebar specimen. This fixture has two bar seats, two lower plates, and two guides machined from steel which are connected with two threaded rods using bolts, and nuts. The conditioned and curtailed bars are placed inside the shear test fixture and tested with a displacement rate such that the test continuous for at least 1 minute and a maximum of 10 minutes until the force reaches 70 % of the ultimate load. The transverse shear strength is determined using the ultimate load and the cross sectional area of the specimen as measured per ASTM D 729 (see above).

1.6.2.3 Horizontal Shear Strength

Next, the FRP rebar product is tested for horizontal shear properties. The horizontal shear test is conducted according to the ASTM D 4475 (ASTM-International, 2012a) standards. This test alone does not suffice for design purposes, but the horizontal shear failure is an indicator for the strength of the resin, and therefore, is a well suited quality control criteria and used for comparison among multiple specimens from the same manufacturer. First, the diameter at the center of the specimen is recorded and the specimens are conditioned at a temperature range from 21 °C to 25 °C and a moisture content between 40 % and 60 % before they are cut to a length of at least 5 times the diameter. A minimum of 5 specimen are tested per sample. The horizontal shear strength is assessed through a three-point load test over a span length that is short enough to prevent bending failure. The load is applied at the center of specimen with a displacement rate of $1.3 \frac{mm}{min}$ until the shear failure is reached via horizontal delamination (failure of the resin). The ultimate load and the break type are recorded and analyzed.

1.6.2.4 Bond to Concrete Properties

In actual engineering applications where FRP rebars are used for internal concrete reinforcement, the bond-to-concrete behavior is of utter most importance because it defines the uniformity or the composite action of the final concrete element. A surface treatment is applied to the rebars to increase the friction at the bond interface or to improve the interlocking effect and to ensure proper bond between the pultruded BFRP rebar and the concrete. Manufacturers have developed different BFRP rebar types, where the surface enhancement vary. For instance the surface may be sand coated, ribbed, or helical wrapped. Ripped rebars resemble the conventional black steel reinforcement and offer a high bond interaction with the surrounded concrete but another production step is needed to add the surface texture which complexes the production. Sand coating is a simpler and faster way to treat the surface of a rebar and offers also good bond quality. The main factors affecting the properties of a FRP rebar include fiber volume, dimensional effects, rate of curing, manufacturing process, and quality control measures during manufacturing (Nanni et al., 2014). Therefore the production is decisive for the later properties of the rebar. The nature of the FRP manufacturing pultrusion process requires a marginal investment to setup (compared to traditional steel mills), while strict control measures, which are necessary to assure quality and consistency of the produced BFRP rebar, may not always be fully implemented. Although their initial cost (raw material and manufacturing costs) and

environmental impact (CO_2 emission during the manufacturing process) may be slightly higher than that of conventional steel, the use of FRP rebars in concrete structures subjected to harsh environments generates a significant potential for extending the service life of these structures and lowering their overall life cycle cost.

While the FRP rebar is reacting over the life-period to environmental influences the durability of a rebar needs to be evaluated. The next Section 1.8 shows the most important aspects to consider when durability of a FRP rebar may be an issue.

1.7   Failure Characteristics of FRP Rebars

The mechanical behavior from FRP rebars differs from steel and has to be considered in the design of reinforced concrete because FRP rebars do not yield and fail sudden. In addition, the fibers are anisotropic, which means that they have different properties in different direction, and the high tensile strength only exists along the fiber axis. The composite FRP rebar (due to its production) also is an anisotropic material and is significantly weaker in the transverse direction then in its longitudinal direction. This property affect the shear strength as well as the bond behavior (ACI Committee 440, 2015).

The failure mode of the FRP rebar itself is strongly dependent on the bond behavior of the fibers and the surrounded resin. Figure 1.9 shows two different failure modes of the matrix after fiber breakage (in tension). The right failure mechanism is not able to transfer the load to the next fiber due to an insufficient bond

Fiber Breakage with Matrix Failure   Fiber Breakage with Slippage
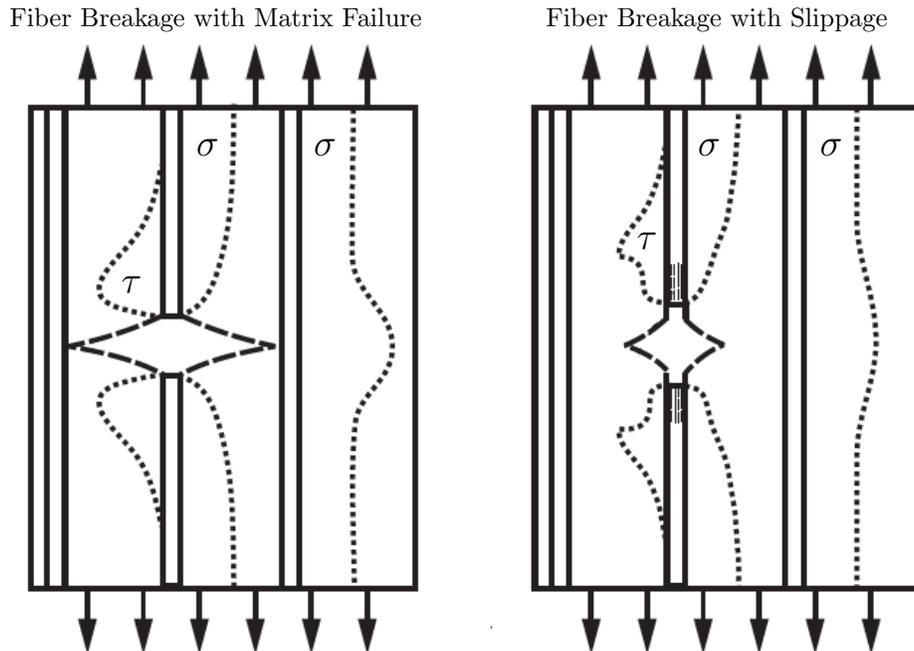
Figure 1.9: FRP rebar tensile failure mechanism (Ehrenstein, 2006)

and results in fiber breakage with slippage. A composite with such a relative low bonding strength between the fibers shows a brush-like formed failure pattern, because the failed fibers delaminate immediately after breakage. The left failure mechanism shows a transfer of the force from the broken fiber to the next one available, which results out of sufficient bonding strength. Not all the fibers reach their rupture strength

at the same time. Individual fibers on the outer side of the rebar break and induce additional tension in the fibers nearby until the brittle failure of the rebar occurs (Ehrenstein, 2006). However, too much bond strength could transfer too much force to the surrounding fibers, which can cause a zip-effect that expands through the whole matrix and lead to an abrupt failure of the composite material. Moreover, a composite with a moderate bond strength is the most advantageous for a high strength material. BFRP rebars are produced to reinforce concrete, especially in harsh environments, where its non-rusting properties compared to conventional black steel reinforcement are advantageous. Therefore, the knowledge of the interactions of the rebars and concrete is essential. The following subsection 1.9 is listing different failure mechanisms of concrete reinforced with FRP rebars.

1.8   Durability of FRP Rebars

Harsh environments have an influence on the properties of a FRP rebar. Because of its reaction to outer influences, the durability of FRP rebars is an important aspect and has to be considered in the designing process before failing suddenly and brittle due to influences occurring over the life time. FRP rebars are susceptible to varying amounts of strength and stiffness changes in the presence of environments before, during, and after construction. Environments can include for instance, water, ultraviolet exposure, elevated temperatures, or solutions (alkaline, acidic, or saline). Depending on the condition the strength of the FRP may change (ACI Committee 440, 2015). To consider long-term exposure to the environment ACI 440 provides reduction factors for various fibers and exposure conditions listed in Table 1.4. Currently, the

Table 1.4: Environmental reduction factor for various fibers and exposure conditions

Exposure condition	Fiber type	Environmental reduction factor C_E
Concrete not exposed to earth and water	Carbon	1.0
	Glass	0.8
	Aramid	0.9
Concrete exposed to earth and water	Carbon	0.9
	Glass	0.7
	Aramid	0.8

design code includes carbon, glass and aramid fibers. The table provides two exposure conditions where fibers are exposed to earth and water or not. Due to outer influences the tensile strength, creep rupture and fatigue endurance can be reduced. Therefore, after the environmental situation is set, the tensile strength and strain has to be multiplied with the reduction factor C_E (last column in table) which reduces the design value or not in the case of carbon fibers in concrete not exposed to earth and water. Nevertheless, FRP composites are resistant in harsh environments, such environment as well as acidic and alkali ones could deteriorate the interface of fibers and matrix if they get in contact directly. For instance, acid diffuses into the macromolecule structure of the polymer and degrades the matrix. In addition, heat, moisture and air pollution influence the mechanisms of degradation and the subsequent results of aging (Bagherpour, 2012). Serviceability criteria or fatigue and creep rupture can control the design of concrete members reinforced with FRP rebars in many cases. Especially aramid FRP (AFRP) and glass FRP (GFRP) are emphasized in the design code because of low stiffness characteristics.

Though FRP rebars made from Basalt fibers are established as a promising replacement for CFRP and GFRP, the durability characteristics and its long-term behavior in concrete structures is not fully understood. For concrete elements exposed to harsh environmental conditions like alkaline, saline, acidic, and de-iodized environments, FRP rebars appear to be the default alternative. But the durability of FRP materials (specifically basalt) in these harsh environments is one of the most important material specific properties because it is often the primary reason for the use of this technology. While the high pH environment created by the cementitious matrix in concrete provides corrosion protection for conventional black steel rebars, the same high pH environment may attack FRP products and cause load capacity degradation. Accordingly, FRP rebars inside concrete elements situated in harsh environments are often exposed to multiple conditions or to a combination of chemically degrading elements simultaneously. The interaction of these combined conditions on FRP rebars are still not fully understood and research in this area is still needed. However, initial efforts have been made and some of the completed projects are summarized below.

According to Wu et al. (2014), the durability of BFRP rebars exposed to alkaline solutions is less than the durability in saline, acidic, and de-iodizes solutions when tested at 20 °C, 40 °C, and 55 °C. The degradation process of FRP rebars seems to be under control if the sustained load levels are kept below 20 % of ultimate tensile strength, but starts to accelerate beyond the 20 % threshold. According to Wu et al. (2014) findings, it takes 16.1 years for an alkaline solution to reduce the tensile strength of BFRP rebars by 50 %.

A study conducted by Lu et al. (2015) compared virgin to aged, pultruded BFRP plates and rebars to measure the effect of thermal aging (at 135 °C and 300 °C for four hours) on the longitudinal tensile strength and the inter laminar shear properties. At 300 °C, the resin decomposed thermally. As the immersion temperature and thermal aging was increased, the mechanical properties of BFRP plates notably decreased. The degradation process of aged rebars immersed in alkaline solution and distilled water accelerated due to thermal aging. while rebars aged at 135 °C, and 300 °C degraded by 62.3 %, and 74.1 % when exposed to high alkaline solution, the degradation process for un-aged BFRP bars exposed to high alkaline solution for three months at 60 °C was accelerated by 43.2 %.

Altalmas et al. (2015) studied the bond-to-concrete durability properties of sand coated basalt fiber reinforced polymer (BFRP) rebars and glass fiber reinforced polymer (GFRP) rebars via accelerated conditioning in acidic, saline, and alkaline solutions for 30 days, 60 days, and 90 days. The variations in slip of BFRP and GFRP bars after conditioning were negligible. The results showed that the bond strength of BFRP immersed in acid solution for 90 days was reduced by 14 % compared to bond strength of un-aged BFRP rebars, and the bond strength of rebars immersed in ocean water and alkaline solution for 90 days was reduced by 25 % in comparison with un-aged rebars. While the bond strength of GFRP rebars reduced by 25 % after acidic exposure, it reduced by 17 % after exposure to alkaline and saline environments in comparison with un-ages rebars.. All specimens failed in inter-laminar shear when tested for pull out strength.

Wang et al. (2017) tested tensile strength and Young's modulus properties of BFRP and GFRP rebars exposed to seawater and sea sand concrete (SWSSC). The rebars were exposed to normal SWSSC (N-SWSSC), and high performance SWSSC (HP-SWSSC) at room temperature, 40 °C, 48 °C, and 50 °C for 21 days, 42 days and 63 days. Damaging mechanisms were determined by using scanning electron microscopy (SEM), changes of microstructure were characterized via X-ray computed tomography (CT), and energy dispersive X-ray spectroscopy (EDS) was used to compute chemical elements after exposure. Sodium Hydroxide (NaOH, 2.4 $\frac{g}{L}$), potassium hydroxide (KOH, 19.4 $\frac{g}{L}$), sodium chloride (NaCl, 35 $\frac{g}{L}$), and calcium hydroxide (Ca(OH) 2 $\frac{g}{L}$) were mixed in 1 L of distilled water to prepare N-SWSSC with a pH level of 13.4. In addition, sodium hydroxide (NaOH, 0.6 $\frac{g}{L}$), potassium hydroxide (KOH, 1.4 $\frac{g}{L}$), sodium chloride (NaCl,

35 $\frac{g}{L}$) and calcium hydroxide (Ca(OH) 0.037 $\frac{g}{L}$) were mixed in 1 L of distilled water to prepare N-SWSSC with a pH level of 12.7. Two BFRP rebar specimens and two GFRP rebar specimens per test group (conditioned vs. unconditioned), with a total length of 760 mm — including steel tube anchors with a length of 250 mm on both ends — were tested for ultimate tensile load. The rebars were embedded in the steel pipe anchors using an epoxy resin, and load rates for these experiments were set to 2 $\frac{mm}{min}$. The ultimate tensile strength of BFRP specimen exposed to N-SWSSC in 32 °C varied from 1317 MPa to 1253 MPa, where as the ultimate tensile strength of BFRP specimen exposed to N-SWSSC in 40 °C varied from 1273 MPa to 1103 MPa, while the ultimate tensile strength of BFRP specimen exposed to N-SWSSC in 48 °C varied from 1257 MPa to 799 MPa, and the ultimate tensile strength of BFRP specimen exposed to N-SWSSC in 55 °C varied from 908 MPa to 352 MPa. The ultimate tensile strength of BFRP specimen exposed to HP-SWSSC in 32 °C varied from 1341 MPa to 1323 MPa, where as the ultimate tensile strength of BFRP specimen exposed to HP-SWSSC in 40 °C varied from 1288 MPa to 1219 MPa, and the ultimate tensile strength of BFRP specimen exposed to HP-SWSSC in 55 °C varied from 1212 MPa to 1046 MPa. The ultimate tensile strength of GFRP specimen exposed to N-SWSSC in 32 °C varied from 952 MPa to 925 MPa, where as the ultimate tensile strength of GFRP specimen exposed to N-SWSSC in 40 °C varied from 903 MPa to 961 MPa, and the ultimate tensile strength of GFRP specimen exposed to N-SWSSC in 55 °C varied from 855 MPa to 848 MPa. The ultimate tensile strength of GFRP specimen exposed to HP-SWSSC in 32 °C varied from 1031 MPa to 1036 MPa, where as the ultimate tensile strength of GFRP specimen exposed to HP-SWSSC in 40 °C varied from 959 MPa to 996 MPa, and the ultimate tensile strength of GFRP specimen exposed to HP-SWSSC in 55 °C varied from 966 MPa to 948 MPa. Nearly no change was found in Young's Modulus for GFRP and BFRP bars after exposure to SWSSC solutions, mainly because that this property depend on the Young's Modulus of the (basalt and glass) fibers, and because the modulus degradation in for fibers in SWSSC solutions may not be significant. When compared to HP-SWSSC, N-SWSSC was more aggressive on both BFRP, and GFRP bars due to the high alkali ion concentration. In high temperature environments, the GFRP rebars were more durable than the BFRP rebars, because of the different resins. Based on the SEM, 3D X-ray, and CT-results, the resin properties of GFRP bars were more stable in SWSSC conditions than the resin used for the tested BFRP rebars.

Patnaik (2009) studied the mechanical properties of BFRP rebars, and moment strength of concrete beams reinforced with BFRP rebars made by the wet lay-up process (see Section 1.4.2) and compare the results with beams reinforced by traditional pultruded BFRP rebars (see Section 1.4.1). The size of the rebars used in this study ranged from #1, rebars to #3 rebars. But more precisely, the rebar diameters for these tests included 4.3 mm, 7.1 mm, 9.8 mm. The average tensile strength of 4.3 mm rebars was 1110 MPa, the average tensile strength of 7.1 mm rebars was noted with 1084 MPa, and the average tensile strength of 9.8 mm rebar measured 1067 MPa. The average modulus of elasticity of 4.3 mm rebars was recorded with 41.1 GPa, while the average modulus of elasticity of 7.1 mm rebar was determined to be 41.4 GPa, and the average modulus of elasticity for 9.8 mm rebars was noted at 45.1 GPa. A total of 13 beams with a cross section of 203 mm × 203 mm, longitudinally reinforced with BFRP rebars, were tested. The beam measured a length of 2135 mm, while the span length was set to 1520 mm. All beams failed in a ductile manner, showing large mid-span deflections. The measured failure loads were greater than, or with in the 3 % range predicted by ACI 440.1R06 (ACI Committee 440, 2006). The results showed that the BFRP bars produced by wet lay-up were as strong as pultruded FRP rebars, but it was noted that the durability characteristics of the BFRP rebars via wet lay-up methods requires additional research.

1.9   Concrete Elements Reinforced with BFRP

Basalt FRP rebars are generally suitable alternatives to steel, epoxy-coated steel, or stainless steel bars in reinforced concrete structures, especially for durability or electromagnetic transparency purposes (Nanni et al., 2014). The occurring failure modes in FRP-reinforced structures are concrete crushing or FRP tensile rupture (Ehrenstein, 2006). In comparison to steel reinforced concrete with its three stages from the uncracked-section, to the cracked section of linear-elastic yield up to the post-yield of reinforcement failure, FRP-reinforced concrete passes only through the first two stages without a post-yielding process (ACI Committee 440, 2007).

Due to the high alkalinity of the concrete (approximately pH 13), the steel is protected against corrosion. For structures in aggressive environments, such as marine structures and bridges exposed to seawater or parking garages exposed to deicing salts, the alkalinity will be reduced. If the alkalinity reduces to a certain pH (approximately 9), the steel depassivates, and corrosion can initiate, which causes concrete deterioration and loss of serviceability (ACI Committee 440, 2015). Due to their advantages in durability aspects, FRP rebars are embedded in concrete for civil engineer applications such as highway barriers, offshore structures, and bridge decks, which are exposed to harsh environments where traditional black steel might corrode during the estimated service time (Brik, 2003). Mainly beams or flexural concrete members are reinforced by FRP rebars at this point. Concrete beams reinforced with BFRP bars achieved moment strengths that are consistent with the relevant properties of the constituent materials and are comparable to those predicted using ACI 440.1R-06 (Patnaik, 2009). However, a lack of experience exist in the use of FRP reinforcement in compression members (columns) and for moment frames or zones where moment redistribution is required (Nanni et al., 2014). Performed SEM analysis by ElSafty et al. (2014) of samples immersed in alkaline solution at elevated temperature for 1000 hours did not show significant signs of degradation. Only the most outer covering of the bar has been affected by the conditioning. Reductions of transverse and horizontal interlaminar shear strength due to conditioning in alkaline solution for 1000 and 3000 hours were detected. A reduction of flexure strength due to conditioning in alkaline solution was recorded after conditioning for 3000 hours with exposure to alkaline solution at 60 °C. Further tests should be required to gather sufficient information for a standardized usage to establish degradation factors for design purposes like they already exist in different codes for other FRP rebars.

Next to the durability factors, environmental impacts of the BFRP rebar production have to be considered to reduce pollution. Because of the high temperature required for production, steel reinforcement has a higher carbon footprint than FRP reinforcement. Recycling instead is not as easy as reproducing steel. Without corrosion, the life cycle costs associated with FRP-reinforced structures are likely lower where steel corrosion should be a concern. A comparison between FRP-reinforced pavement and steel-reinforced pavement over the lifetime determined that FRP reinforcement had a significantly smaller environmental impact than the version with steel (ACI Committee 440, 2015).

While the general properties and components of BFRP rebars are described above, the following chapter offers details about the certification process of FRP rebars and their implementation into national and international codes. Moreover, an analysis of the current BFRP market was conducted to collect information about availability and production processes around the world. The gathered information about the available products shall help to provide recommendations for an implementation of BFRP rebars into the national design codes and for the use of these construction materials in public infrastructure projects.

CHAPTER 2

BFRP REGULATIONS AND MARKET

This chapter provides a details about current regulations for FRP rebars with the focus on basalt fibers and the international BFRP market situation and the available products. The standardization progress in the FRP industry is described in Section 2.1. In addition, Section 2.2 provides a comparison of the different acceptance criteria for the mechanical properties on national and international levels followed by Section 2.3 and 2.4 which summarize the state-of-the-art of the BFRP industry.

2.1   Regulations for FRP Rebars

This section describes the national and international regulations for FRP rebars and its historical development. Several global activities have been completed to implement FRP rebars into design codes and guidelines since the 1980s. In the United States, the initiatives and vision of the National Science Foundation and the Federal Highway Administration promoted the development of this technology, to support research at different universities and research institutions.

In 1991, the American Concrete Institute (ACI) established Committee 440 — FRP Reinforcement. The objective of the committee was to provide the construction industry with science-based design guidelines, construction specifications, and inspection and quality control recommendations related to the use of FRP rebars for concrete structures. In 2001, Committee 440 published the first version of the document "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars". The availability of this document further expedited the adoption of FRP rebars (Nanni et al., 2014). Around the time of the millennium, research projects on fiber reinforced plastics were conducted in many countries (e.g.; Japan, Europe, China, Canada and America) which led to the development of standard documents and national design codes for the use and implementation of FRPs as illustrated in Figure 2.1. The first document that introduced
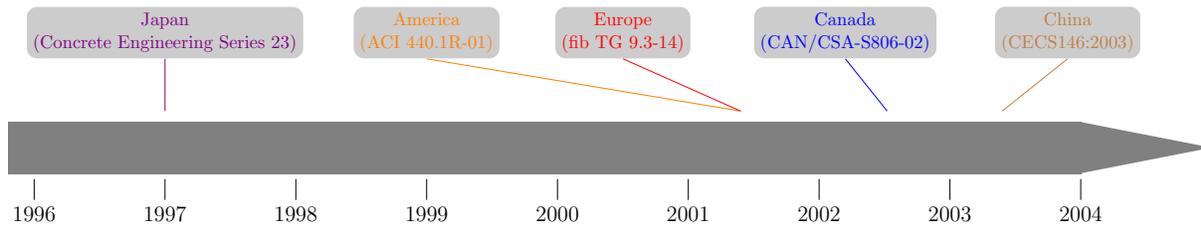
Figure 2.1: Chonology FRP International Code Development

test methods for FRP rebars was "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials", which was published in 1997 by the Japan Society for Civil Engineering (JSCE). ASTM International and the Organization for Standards (ISO) developed standardized test methods related to the use of FRP composites in structural engineering. Model test methods for FRP bars are recommended by the ACI document 440.3R, "Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete and Masonry Structures", effective since 2004, while ear-

lier documents like ACI 440.2R introduced first design recommendations in 2002. Test procedures have also been developed by the Canadian Standards Association (CSA) or the European International Federation for Structural Concrete (fib) (Nanni et al., 2014).

The American Concrete Institute Committee 440 (ACI440) has led the effort to address the technical implementation for GFRP rebars by developing and publishing test methods, specifications, and design guidelines (ACI Committee 440, 2006, 2008a,b, 2012, 2013, 2015). The 2008 version of ACI440 (ACI Committee 440, 2008b) and the 2010 version of the Canadian-CSA Specifications for Fiber Reinforced Polymers (Canadian Standard Association, 2010) were developed to standardize glass, carbon, and aramid FRP bars. The Canadian Standards Association (CSA) has led the western effort for developing specifications and design guidelines for BFRP. The new CSA S807 (Benmokrane, 2018) standard includes FRP bars made from basalt fibers which emphasize the current importance of this material and the confidence of a commercialized usage in the field (Vincent et al., 2013). Similarly, ASTM Committees D30 and D20 have addressed the emergence of this technology by developing a number of test methods (ASTM-International, 2015a) intended to characterize GFRP rebars, while BFRP rebars are not standardized yet in the U.S. Recently, in 2017, ASTM D 7957 with specific guidelines for solid round glass fiber reinforced polymer bars for concrete reinforcement was adopted (ASTM-International, 2017). In addition, the FDOT has developed documents to aid the implementation and design of GFRP rebar technology in the built infrastructure, specifically the expanded Section 932 for nonmetallic accessory materials for concrete pavement and concrete structures (Ruelke, 2014), and more recently the fiber reinforced polymer guidelines (FRPG) (Florida Department of Transportation, 2015; Hurtado, 2018). At the national level, the American Association of State Highway and Transportation Officials (AASHTO) has also developed guides for the use of FRP technology (AASHTO, 2012) for externally bonded systems. It is desired to add BFRP specific criteria to these specifications and guidelines as soon as practical to provide redundant supply chains and additional alternatives. Agencies are interested in BFRP composites because the technology has improved recently (as explained in Chapter 1). Further reasons are properties such as a higher elastic modulus, higher tensile strength and for e.g. the consideration of a more environmental friendly product.

For a design standard to become official, it must be adopted by a model building code or by a regulatory agency. In the United States (and other parts of the world, including the United Nations), the International Building Code (IBC) part of the family of International Codes (I-Codes) is the predominant model code (adopted by all 50 states, Puerto Rico, and the U.S. Virgin Islands) and covers the design and construction of new buildings. (Nanni et al., 2014) Moreover, the International Code Council Evaluation Service (ICC-ES), which is the industry leader in performing technical evaluations for code compliance as part of the International Code Council (ICC) that develops model codes and standards, published the "Acceptance Criteria for the use of GFRP and BFRP rebars for concrete reinforcement", known as AC454 (International Code Council Evaluation Services, 2017). Hence, today any structure that is to be built according to the requirements of the Florida building code, which is based on the model code (International Building Code, IBC), can be realized with BFRP rebar technology.

For the implementation process of a product the existence of a set of protocols and provisions is necessary. Therefore, tests, analysis of the results, and the design have to be conducted. Moreover, ICC Evaluation Services (ICC-ES) develops in partnership with the proposers of new technology-specific documents called "acceptance criteria (AC)" for the purpose of issuing evaluation (research) reports. After it is demonstrated that the product is manufactured under an approved quality control program, the research program outlined in the AC is conducted by a certified independent laboratory, its outcomes are evaluated by ICC-ES, and,

assuming compliance, a research report is issued. Thus, the alternative material/technology now has official recognition (Nanni et al., 2014).

Through the development of standardized test procedures and available design documents, it became feasible to compare and evaluate standardized material performances which lead to the development of acceptance criteria for different products. These acceptance criteria are described in Section 2.2 below.

2.2   Acceptance Criteria for FRP Rebars

This section lists the acceptance criteria for the most important certification documents for FRP rebars. Acceptance criteria for FRP rebars include mechanical, physical, and durability requirements for implementation and usage in civil structures on a state, national, or international level. Physical requirements include testings of FRP properties such as the fiber content, glass transition temperature, measured cross-sectional, and durability tests consider the moisture absorption, the resistance to alkaline environments and the void content (International Code Council Evaluation Services, 2016). This section provides mechanical acceptance criteria for FRP rebars because this research project focuses on the mechanical tensile strength of BFRP rebars. Required criteria are listed in Table 2.1 for Section 932 in the State of Florida for FRP rebars, ASTM D 7957 on a national level for glass FRP rebars, and on the bottom for AC454 on an international level for glass or basalt FRP rebars. It can be seen that the table matches the required mechanical proper-

Table 2.1: Required test procedures and specimen quantities per acceptance test and production lot

		Tensile		Shear		Bond
		Ultimate Load ASTM D7205	Elastic Modulus ASTM D7205	Transverse ASTM D7617	Apparent Horizontal ASTM D4475	Strength ACI 440.3R
FDOT 932-3	Bar Size	each	each	each	each	smallest (5), median (5), largest (5)
	Specimen per Lot	10	10	5	5	15
	Lots	3	3	3	3	3
ASTM D7957	Bar Size	each	each	each	each	each
	Specimen per Lot	8	8	8	8	8
	Lots	3	3	3	3	3
AC454	Bar Size	each	each	each	each	smallest (5), median (5), largest (5)
	Specimen per Lot	5	5	5	5	15
	Lots	5	5	5	5	1

ties according to the official test procedure (ASTM and ACI) with the different available documents (FDOT Section 932 and AC454) that require these tests. The table details how many specimens per lot and how many lots have to be considered for each test and bar size. The different certification documents require testing of three to five to ten samples per production lot. In summary, each certification document requires a comparable amount of specimens and test repetitions per specimens to gather sufficient data for a general use in the field.

According to the normal (Gaussian) distribution to estimate the mean strength with a 95% confidence

level, within 5 ksi margin of error, a sample size of at least five rebars are needed as stated in ACI 440.1R-01. To obtain a 99% level of confidence at the same margin of error, at least nine rebars are needed. To determine guaranteed values of strengths and strains at a 99 87% probability requires testing of 25 specimens (Kocaoza et al., 2004). The guaranteed strength or strain is to be derived based on statistical analysis if fewer test specimens are tested, or the distribution is not a normal distribution (ACI Committee 440, 2006). Additionally, to the required amount of test specimen the certification documents (FDOT, ASTM, and AC454) present rebar size and tensile load requirements for FRP rebars. All three specifications define the minimum and maximum cross-sectional dimensions and the minimum guaranteed tensile strength values per rebar size as shown in Table 2.2. It can be seen that information for the rebar sizes and corresponding limits

Table 2.2: Required sizes and tensile loads of FRP reinforcing bars

Bar Size Designation	Nominal Bar Diameter	Nominal Cross-Sectional Area	Measured Cross Section		Minimum Guaranteed Tensile Load	
			Minimum	Maximum	GFRP Bars	CFRP Bars
#	in.	in.^{2}	in.^{2}	in.^{2}	kip	kip
2	0.250	0.049	0.046	0.085	6.1	10.3
3	0.375	0.11	0.104	0.161	13.2	20.9
4	0.500	0.20	0.185	0.263	21.6	33.3
5	0.625	0.31	0.288	0.388	29.1	49.1
6	0.750	0.44	0.415	0.539	40.9	70.7
7	0.875	0.60	0.565	0.713	54.1	-
8	1.000	0.79	0.738	0.913	66.8	-
9	1.128	1.00	0.934	0.388	29.1	-
10	1.270	1.27	1.154	1.385	98.2	-

for the measured cross-sectional area, and the minimum strength values for tensile capacities are listed. The span between the min and max cross section is included because of differences in surface enhancements and production processes. The last column lists minimum guaranteed tensile loads for each rebar size for GFRP and CFRP bars. The only difference between the FDOT Section 932, the ASTM D 7957 and the AC454 is that the AC454 provides additional minimum tensile loads for the measured diameters, which are a little higher than the minimum loads calculated by using the nominal diameter.

While different production techniques and processes exist in the FRP rebar market, these established acceptance criteria allow manufacturers to target specific properties. Nevertheless, BFRP rebars were produced before these acceptance criteria were available and manufacturers followed very individual and proprietary production sequences. Accordingly, the market is very diverse with various products, and new manufacturers enter the market quickly. However, an overview of the current BFRP rebar industry follows below.

2.3   Global BFRP Rebar Manufacturer Analysis

This section provides information about the BFRP rebar manufacturers, their production logistics, and the available products. The first FRP rebar became commercially available in the late 1980s, when the market demand for electromagnetic-transparent reinforcing systems increased. At that time, the technology

was developed enough to provide a viable solution as internal reinforcement for concrete structures (Nanni et al., 2014). Afterwards, the technology gained traction and different BFRP rebar manufactures were established around the world with a majority of the early companies in russia. European and Northern American companies followed the trend of manufacturing FRP rebars, while the basalt fiber was imported from areas with an easier access to basalt rock sources such as Asia or parts of Europe. In the text below, the current BFRP rebar industry profile is described; first based on general data provided in the literature, and then based on marked data gathered directly from manufacturers.

Markets and Markets (2016) conducted a study that projected the market growth up to \$91 million until 2021. This growth is fueled by the increasing demand for the renovation and strengthening of new and existing structurally deficient bridges especially in harsh environments near the coast or connecting islands to the mainland. For instance, according to the National Bridge Inventory (NBI), more than 146.000 bridges are structurally deficient or functionally obsolete in the U.S. as of 2010. From February 2003 to December 2013, FDOT District 7 conducted a study that evaluated the current status and the required repair costs of 54 (20 steel and 34 concrete) bridges. It was concluded that 76% of all repair cost would be necessary to alleviate damages due to corrosion (Fallaha et al., 2017). Thus, the use of FRP rebars in these applications has the potential to reduce the life cycle costs, thereby enhancing service life and safety.

The Floodway Bridge (Canada) is one of the largest bridges constructed with FRP rebars. In addition, The Florida Keys Bridges (U.S.) is one of the prominent examples for the use of CFRP rebars to strengthen structurally deficient bridges and bridge elements. Many similar projects, in which FRP rebars are used as internal concrete reinforcements, are executed in the U.S. and Canada (Markets and Markets, 2016). Nevertheless, the lack of confidence in durability in aggressive environments (for 75 to 100 years of service life), limitations on strength due to low design resistance factors related to lack of ductility or due to degradation of properties over time, are challenges for the implementation. Moreover, creep-rupture mechanisms limit the service limit state design, and the comparatively low elastic modulus (relative to conventional black steel) leads to greater deflection and larger crack openings (Fallaha et al., 2017). Accordingly, a new challenge will be the development and implementation of new inspections and repair methods.

North America is one of the main leaders in the world market for FRP rebars and has the fastest-growing demand worldwide, because of its high economic growth rate, numerous construction projects, and capacity expansion, although the basalt fibers are mostly produced in Russia and China and have to be imported. In 2018, the first basalt fiber production plant in North America was built in North Carolina. Raw basalt rock is melted and shaped into basalt fibers. The produced fibers are combined with a resin in one process to produce the final FRP rebar shape. At this time, seven manufacturers produce BFRP rebars in the U.S. either exclusively or in combination with other FRP rebar. Figure 2.2 provides a visualization of BFRP rebar manufacturer density world wide, and it can be seen that (to this date and to the knowledge of the author) 23 manufacturers commercially produce BFRP rebar products year round. It is reported by Galen Panamerica, that there are hundred's of "garage BFRP operations" that pultrude products in Russia and Ukraine during the warmer months. The circles on the map indicate number (per country) and location of manufacturers. The highest density can be found in North America with nine manufacturers (seven in USA and two in Canada). A total of six BFRP rebar producers are located in Europe (two in Germany, one in Norway, one in Ukraine, one in Austria, and one in England), while eight Asian manufacturers exist (four in China, three in Russia, and one in India).

As part of this research project, 23 BFRP manufacturers from ten different countries were contacted to participate in a survey with the aim to collect manufacturer-specific data about production logistics, the

Figure 2.2: BFRP manufacturer locations

produced BFRP rebar product types, their physical features, and the manufacturer guaranteed material properties. All manufacturers in these 23 countries were contacted via email, phone calls, or personal meetings. These initial conversations were followed by survey with a BFRP rebar production-specific questionnaire. Details about the contacted BFRP rebar manufacturers and a copy of the survey that was shared with them can be found in Appendix A. Based on the provided information, the state of the market was analyzed and the data is presented below to provide additional context for the technology, within a national and international framework. Table 2.3 lists the production and rates per manufacturer. The most left column in the table lists the contacted manufacturers in this survey. Data about their first BFRP rebar production stocking quantities and the production rates are listed in the table (for those manufacturers who responded to the survey) Based on the received data from ten manufacturers, it can be inferred that just two manufacturers started their BFRP production before the year 2000. Furthermore, over 50% of the manufacturers started the production of BFRP rebars after 2007. The majority stock their products in large quantities and it can be seen that the production rates are significantly higher in the Asian and European countries compared to the United States. Kodiak Fiberglass Rebar is the company that (currently) provides the largest production capacity on the North American continent for BFFP rebars with a production output of $4,600 \ m/d$. In comparison the Russian company Armastek is able to produce $50,000 \ m/d$, which is about 11 times more. Figure 2.3 shows a diagram that compares the different stocking options used by the various manufacturer in the industry. The part of the pie chart with solid diagonal lines identifies 50% of the companies, which stock rebars in large quantities ($> 500 \, \mathrm{m} (1640 \, \mathrm{ft})$), while the area with the dashed diagonal lines, signifies with 20% the stocking of small quantities ($< 500 \, \mathrm{m} (1640 \, \mathrm{ft})$), and the dotted part represents manufacturers, who produce rebar on demand (30%). The next Figure visualizes the production rates of the manufacturers. The production rates are listed on the y-axes in ft/d (left axis) and m/d (right axis). Three character IDs (see Table reftab:BFRP rebars produced by manufacturer) for each manufacturer (which participated in the survey) are listed along the x-axis. The bars visualize the lowest production rate for ASA TEC GmbH (ASA) with $960 \, \mathrm{m/d} \ (3150 \, \mathrm{ft/d})$ and the highest production rate for Armastek with $50\,000 \, \mathrm{m/d} \ (164\,000 \, \mathrm{ft/d})$. The average production of all listed BFRP rebar producers is $13\,000 \, \mathrm{m/d} \ (42\,650 \, \mathrm{ft/d})$.

Table 2.3: Production logistics and rates per manufacturer

Manufacturer	First BFRP bar	Production Logistic†	Production Rate	
	Year		m/d	ft/d
No Rust Rebar Inc.	Before 1990	Stock in large quantities	4,600	15,000
Smarter Building System	2000	Stock in large quantities	6,000	19,700
Neuvokas Corp.	-	-	-	-
KODIAK Fiberglass Rebar	2014	Stock in large quantities	9,200	30,000
Advanced Filament Technologies	1998	Stock in large quantities	3,000	9,800
US Basalt	-	-	-	-
Proven Performance Chemicals	-	-	-	-
Pultrall Inc.	2010	Production on demand	8,800	28,800
Armkar Inc.	-	-	-	-
Incotelogy GmbH	-	-	-	-
Deutsche Basalt Faser GmbH	2017	Stock in small quantities	14,000	45,900
ASA.TEC GmbH	2012	Production on demand	960	3,150
Basalt Technologies UK Limited	-	-	-	-
ReforceTech AS	-	-	-	-
Technobasalt-Invest	2010	Stock in small quantities	16,000	52,500
Galen Panamerica	2001	Stock in large quantities	20,000	65,600
Rusnano (TBM)	-	-	-	-
Armastek	2007	Production on demand	50,000	164,000
GMV	-	-	-	-
Phoenix New Material Co., Ltd.	-	-	-	-
GBF Basalt Fiber Co., Ltd	-	-	-	-
Huabin General Machinery Co,Ltd.	-	-	-	-
Flips India Engineering	-	-	-	-

† Small quantities below 500m (1640ft.); Large quantities over 500m (1640ft.)

17 questions about the chosen production logistics made up the first part of the BFRP rebar manufacturer survey, the second part was aimed at specific product properties and the following Section 2.4 summarizes the findings from part two.

2.4   BFRP Products Database

The data collected through the second part of the survey provides centralized information about parameters such as cross-sectional shape, resin type, surface enhancement, and produced diameters. The answers to all survey questions reflect the currently available products and the related parameters; cross-sectional shape, resin type, surface enhancement, and produced diameters. The acquired data are shown in Table 2.4. Based on the manufacturers who shared their company-specific data, the dominant cross-sectional shape is round and solid. The only exception is the German company Deutsche Basalt Faser GmbH, which produces round hollow rebars instead. In addition, the majority of the BFRP rebar producers focus exclusively on the production of basalt FRP rebars. However, four companies also produce rebars with other fiber types like glass or add basalt fibers afterward to their portfolio because the production sequences and processes for these rebars are very similar. Besides vinyl ester, the most used resin type is epoxy: it is one of the more expensive types with a long curing time. The surface enhancement is the feature which varies the most
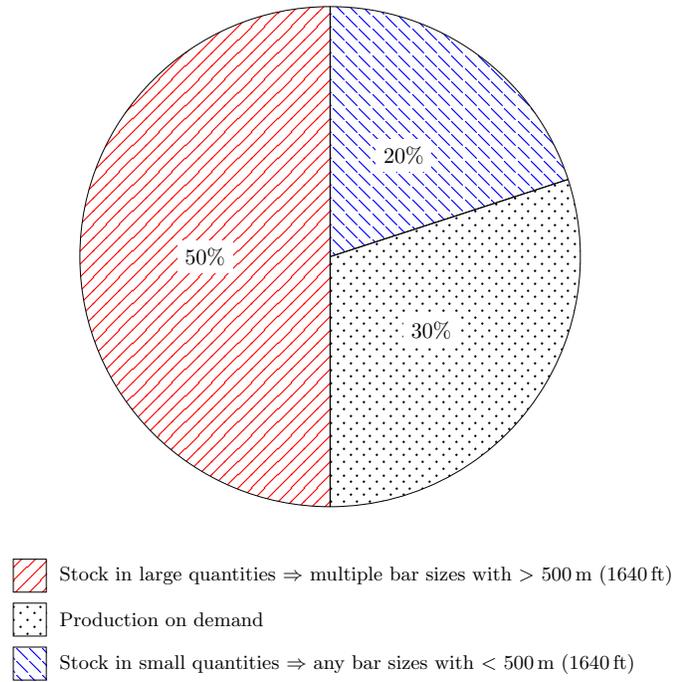
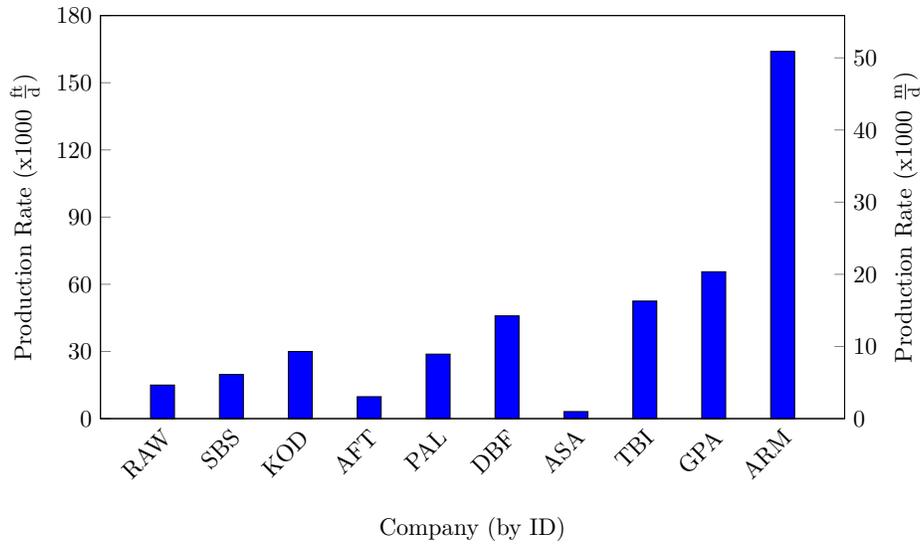Figure 2.3: Production and storage strategies chosen by BFRP manufacturers

Figure 2.4: BFRP production rates (as reported by manufacturers)

between the listed manufacturers. The use of helical wrap, sand coat, or a combination of both is applied based on the manufacturer. The various produced rebar diameters differ in quantities/availability between manufacturers. Based on the preferred measurement system in the production country (metric vs. imperial), the available nominal rebar diameters differ. Some rebar producers only produce a single size, while other

Table 2.4: BFRP rebars produced by manufacturer

Manufacturer	Cross-Sectional Shape	Fiber Type	Resin Type	Surface Enhancement	Produced Diameters
RAW	Round (solid)	Basalt	Epoxy	Helical wrap & Sand coat	#1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
SBS	Round (solid)	Basalt	Epoxy / Vinyl Ester	Helical wrap	#1, 2, 3, 4, 5, 8
NVC	Round (solid)	Basalt	Epoxy	-	#3
KOD	Round (solid)	Basalt/Glass	Epoxy / Vinyl Ester	Helical wrap/rib & Sand coat	#2, 3, 4, 5, 6, 7,8
AFT	Round (solid)	Basalt	Epoxy	Helical wrap	#1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
USB	-	Basalt	-	-	-
PPC	-	Basalt	-	-	-
PAL	Round (solid)	Basalt/Glass	Epoxy	Sand coat	#2, 3, 4, 5, 6, 7, 8, 9, 10, 11
AKI	-	Basalt	-	-	-
ICT	-	Basalt	-	-	-
DBF	Round (hollow)	Basalt	Thermoset	Sand coat	#1, 2, 3, 4, 5
ASA	Round (solid)	Basalt	Vinyl Ester	Helical rib	#2, 3, 4, 5, 6, 8
BTL	-	Basalt	-	-	-
RAS	-	Basalt	-	-	-
TBI	Round (solid)	Basalt	Epoxy	Helical rib	4 mm to 14 mm
GPA	Round (solid)	Basalt/Glass	Epoxy	Sand coat	#1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
RSN	-	Basalt	-	-	-
ARM	Round (solid)	Basalt/Glass	Epoxy	Helical wrap & Sand coat	#1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
GMV	-	Basalt		-	-
PNM	-	Basalt	-	-	-
GBF	-	Basalt	-	-	-
HGM	-	Basalt	-	-	-
FIE	-	Basalt	-	-	-

producers have the capacity to supply a wide array of rebars (#1 to #12 or higher). Rebar #3 with a diameter of 3/8 inch (10 mm) and rebar #5 with a diameter of 5/8 inch (16mm) are the two most commonly available, and therefore, most used diameters in civil applications.

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