# BOND PERFORMANCE OF BASALT FIBER REINFORCED POLYMER BARS AGAINST AGGRESSIVE ENVIRONMENT IN CONCRETE

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Has been accepted towards the partial fulfillment

of

the requirement for the award of the degree of

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by

Saqib Hussain

This is to certify that we have examined the above MS thesis and found that it is complete andsatisfactory in all respects and that any, and, revisions required by the thesis examination committee have been made.

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# ACKNOWLEDGEMENTS

Since I got admission as a graduate student at the NUST Institute of Civil Engineering, National University of Science and Technology, H-12 Islamabad, this period was one of the wealthiest and most exciting years of my life. On this journey, I met many people with whom I learned a lot and whom I will never forget. The following lines are dedicated to thanking the ones that contributed to my studies and my project.

First, I would like to thank my supervisor, Dr. Musaad Zaheer Khan, Assistant Professor, NUST Institute of Civil Engineering, for his generosity, kindness, flexibility, cooperation, and guidance. Despite a hectic schedule, he went beyond the call of duty to provide excellent and prompt guidance for unconditional support and encouragement throughout my project work. I must also acknowledge his availability, dedication, guidance, and reviewing of the drafted report.

I also owe a debt of gratitude to my project evaluation committee members/examiner, Engr. Dr. Muhammad Usman, Dr. Hamad Anis, and Dr. Usman Hanif. Their constant support, intellectual, logical comments, suggestions for improving my thesis, and help during the execution of the computational work, improved the quality of work.

I am indebted to my parents for the endless encouragement, patience, and support they have given me over the past year and my entire life. Thanks for reminding me that knowledge is power; experiences are priceless.

I am grateful to my friends and colleagues who provided continual moral encouragement and never gave up on me when it seemed like this project would never be completed. At this stage, I would also like to thank my friends and colleagues, Engr. Sajid Rasheed, Engr. Usman Tanveer, Engr. Hassaan Saleem, Engr. Jamman Sahid, and Engr. Shoaib Nasir for their constant support and help during the coursework and research work.

***Wednesday, February 2, 2022*** ***Saqib Hussain***

# ABSTRACT

Concrete has been utilized in building for many decades because of the need for reinforcements because of its fragile nature. Bamboo, wire mesh, and structural steel have all been used to reinforce concrete during the last few decades. Regarding commercial and subterranean applications of concrete-reinforced steel (CRS), corrosion is more likely to occur. Rusted steel used in concrete rehabilitation is time-consuming and expensive. GFRP, CFRP, and AFRP bars are just a few of the many choices that researchers have advised thus far. Apart from the superior strength-to-weight ratio and low corrosion susceptibility, these bars surpassed rebars in every other regard. However, further research needs to be done to properly understand how the BFRP bars respond to a variety of concrete mixtures. Basalt fiber reinforced polymer bars (BFRP) is produced by mixing thin basalt fibers with resin to make a polymeric matrix using the pultrusion method. Several variables, including the kind of concrete, bar size, embedment length, and a variety of harsh environments, are being altered to examine the bonding performance of BFRP bars. The pull-out performance of three distinct bar diameters (12.7, 15.9, and 19mm) was investigated by adjusting three different embedment lengths (5db, 10db, and 15db) in various concretes, including normal strength, high strength, and geopolymer concrete. A seawater environment and an alkaline environment were used to evaluate each scenario. Bond strengths of 22.5, 20.99, and 15.32 MPa were observed in high strength, normal strength, and geopolymer concrete, respectively, tested in an environment that was under controlled conditions. High strength, normal strength, and geopolymer concrete retained 82 percent, 79 percent, and 76 percent of their bond strength, respectively, in an alkaline environment. When exposed to seawater, high strength, normal strength, and geopolymer concrete

showed bond strength retention of 80%, 76%, and 79%, respectively. The bond strength of the BFRP bar was predicted using the Fib bulletin method for 50 years

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# INTRODUCTION

## 1.1 Background

Many researchers have suggested the use of efficient and effective materials as a trend to replace conventional concrete materials as innovation in the construction sector progresses. In the construction industry, concrete is one of the most often used materials due to its low cost, high compressive strength, and ease of shaping. Each material has upsides and downsides. Concrete cannot be utilized in constructions wherever tensile resistance is necessary due to its brittleness and fragility in tension. Concrete is fortified with additional materials that have higher tensile resistance to overcome this flaw. Prior to the development of concrete technology, bamboo was employed as reinforcement in concrete; however, steel has since been suggested as a superior material. Steel replaced many other building materials to be utilized as reinforcement in concrete owing to its improved efficiency in tension and ductile nature. With a pH of 13–14, concrete is alkaline, but over time, it becomes less so. When deicers are used, the concentration of chloride ions in the concrete rises, which might cause the PH to fall. Concrete contains calcium hydroxide, which slowly reacts with environmental carbon dioxides to form a hydration product. Calcium carbonate is produced because of the reaction with alkaline portlandite concrete. The pH of concrete decreases when chloride concentration rises, and concrete's alkalinity is consumed. The steel passive protective coating disintegrates once the PH of concrete falls below 9.5, and the corrosion process begins. Iron oxide, an expanding byproduct of the corrosion of steel in hardened concrete, results in tension in the concrete, which leads to failure.

Steel corrosion not only reduces its cross-sectional area but also degrades the concrete. Repair on concrete and steel is a costly and hectic process, which is the reason researchers are working on the better reinforcement option for the past few decades. Fiber-reinforced polymer (FRP) bars, because of their great tensile properties, are one of the emerging solutions. Many types of FRB bars, such as glass fiber reinforced polymer (GFRP) bars, carbon fiber reinforced polymer (CFRP) bars, and aramid fiber-reinforced polymer (AFRP) bars have been evaluated in the past as a reinforcement in the concrete. Basalt fiber reinforced polymer (BFRP) bars have better tensile properties and a low weight to strength ratio as compared to the above-discussed options its resistance against corrosion makes it a suitable replacement for steel.

## 1.2 Research significance

Basalt fiber reinforced polymer (BFRP) bars supersedes steel bars in tensile properties, but other parameters, such as bond strength, are an important parameter to study before using it commercially. To use BFRP bars in concrete, its interfacial surface bond with concrete should be satisfactory. Concrete is used in many types of environments, such as industrial environments, alkaline environments, and coastal environments. Bond performance of steel with concrete degrades as it is used in a different aggressive environment, so it is important to study the BFRP bars in a different aggressive environment. The bond performance also varies with the strength of concrete, which demands BFRP bars to be studied in different strength concrete. Geopolymer polymer concrete is a modern technology in the concrete industry that is environmentally friendly also involves the usage of aggressive chemicals for the activation of cementitious material. As green concrete is needed in the future because of an increase in carbon footprints, the bond performance of BFRP bars should also be studied by varying its strength and exposed environments. Concrete performance degrades with the age of concrete, so bond performance over the age of concrete raises the question of the use of BFRP bars in concrete. Bond stress of BFRP bars throughout the life of concrete is, therefore, a particularly important parameter to study, especially when exposed to different environments.

## 1.3 Research objectives

This research focuses on the following objectives.

- To study the bond performance of BFRP bars reinforced in normal strength and high strength concrete.
- To test the bond performance of BFRP bars reinforced in geopolymer concrete.
- To check the bond performance of the BFRP bar in each type of concrete when exposed to different aggressive environments.
- To study the bond stress of BFRP bar's varying diameters and bonding length.
- To analyze the stress-stress relationship of BFRP bar in different concretes and in different environments.
- To analyze the relationship between bond stress to concrete strength.
- To predict the future bond stress of BFRP bars in different concrete when exposed to different environments.

## 1.4 Thesis Structure

The thesis starts with an introductory chapter named as the introduction and numbered as the first chapter. In the very first chapter, a brief introduction of problems and needs is described for the use of basalt fiber reinforced polymer bars. Research objectives are precisely described after the research significance is described. Chapter 2, named "Literature review" provides the background knowledge about BFRP bars and other FRP bars. This chapter also reviews the research of different researchers and explains the literature gap that needed to be filled. Complete knowledge of BFRP and its structure is also explained. Chapter 3 is titled "research methodology" and in this chapter, research is explained. Different concretes and their mixed designs are also discussed in detail. Geopolymer concrete its mixed design and guidelines are also explained in this chapter. Unconditioned, seawater, and alkaline environments and ways of producing these environments are explained in this chapter. The different number of samples, with varying bar diameters, bonding lengths, concrete types, and environments, are also explained. In Chapter 4, results are explained, and discussion is done on different findings such as stress-slip relationship, the relationship between bond stress and concrete strength, future prediction of bond stress, and bond performance of BFRP bars against different aggressive environments. So, this chapter was named "Results and discussion". In chapter 5, all the findings, behaviors, and relationships of BFRP against different parameters are summarized. Future recommendations are also given in this chapter. This chapter is titled "Conclusions and reconditions". The last chapter comprises references used to support this research work and is named "References".

# LITERATURE REVIEW

## 2.1 Fiber-Reinforced Polymer (FRP)

A Synergistic Material which is formed by mixing of thin fibers with a polymeric matrix. This Synergistic material is referred as Fiber Reinforced Polymer (FRP) (Badifu et al. 2020). Concrete become less dense, corrosion resistive, non-magnetic, insulator, etc. by adding FRPs materials. These properties make FRPs to use as reinforcement in concrete. Density of FRPs ranges 1.25 to 2.1 gram per cm3 which is just 25% of the steel density. Due to low density of FRP's material, it is easy to transport and reduce dead weight of the structure. Mechanical properties of the FRP's depend on fibers to FRP composite quantity, manufacturing methodology, curing conditions, quality control parameters. Multiple factors influence the mechanical behavior of FRP materials like the fibers ratio to the FRP composite amount, curing rate, type of manufacturing process used, quality control tolerances, etc.

Thermal expansion of FRP's varies direction to direction which is a drawback. It has different value in longitudinal direction as compared to transverse direction. Thermal expansion of former direction influenced by the mechanical properties of FRP's, and later direction influenced by the resins. This behavior of FRP makes it anisotropic in nature. Due to being anisotropic, FRP's stiffness in transverse is less as compared to the longitudinal direction. Tensile testing approach is not suitable because there might be high stresses in transverse direction which makes it brittle nature because of local stresses formation.

Masmoudi appraised that there is no long term solution/method for determining the tensile behavior of FRP's (Masmoudi 1996). Whereas the parameters for tensile testing specimen and steel tubes is well defined by (Method 2021). Methods for determining the stiffness and tensile behavior of FRPs are also discussed in ACI 440. 3R (2004).

Eshani et el and (Adhikari 2009)) explained the FRP bar's tensile strength. He described the ultimate tensile strength isn't the inherent property of the FRP materials, but it depends upon the geometry and the bar size. This type of behavior occurs because of the anisotropic nature of the FRP bars. Outer fibers will take more stress than the inner fibers when the material is applied to the axial tensile loading and, as a result, the material will lose its load-taking capacity. (Kocaoz, Samaranayake, and Nanni 2005) described that with the increase in the bar diameter its tensile load taking capacity will decrease.

## 2.2 Production of FRP bars

Different type of fibers i.e., Glass, Basalt, Carbon etc. can be used for production of FRP's reinforcement bars. These FRP's reinforcement bars have high tensile strength as compared to normal steel reinforcement. FRP's are brittle in nature which its reinforced bars will not show yielding instead will fail directly provided their response is purely linear/elastic until the rupture appear. Glass Fiber Reinforced Polymer are less expensive as compared to the Carbon Fiber Reinforced Polymer. Mechanical properties such as tensile strength etc. of Basalt Fiber Reinforced Polymer is better than the Carbon Fiber Reinforced Polymer. (Zych and Wojciech, 2012). Due to higher mechanical properties and cost effective, GFRP's is most popular among all industries and opening door for researchers to work on other fibers (ACI Committee 440, 2007). Today, the researchers are focusing on BFRP's which is better than GFRP's in all aspects. One of the advantages of FRP's is its corrosion resistance property.

FRP materials have been incorporated into a wide range of applications as bridges and retaining walls. These materials prove to be the best when the structures are exposed to aggressive media. There are multiple procedures to manufacture the FRP materials with the pultrusion process being the most used of the list. It is a consistent creation process that can deliver up to five feet of flimsy walled filaments. FRP composites can be delivered into three distinct materials: structural profiles, discrete fibers, and solid plates and bars.

## 2.3 Bond durability between FRP bars and concrete

It is worth mentioning that in literature, there is a contradiction regarding dependance of bond strength on concrete properties. Some researchers suggest bond strength as function of compressive strength of the concrete whereas some presents bond strength is independent of concrete strength. (Davalos, Chen, and Ray 2008). Resin matrix, its properties and formation have importance in regard that it controls the movement of stress to FRP rebars. Aggressive environment may affect the resin matrix and ultimately the FRP properties. If surface treatment is taken for FRP reinforcement, durability of the concrete is compromised. Similarly, this can also cause the void creation, crack propagation in production phase. It is also worth knowing that micro level cracks in FRP material during production phase, will affect dominantly the bonding of FRP reinforcement with concrete. It will weaken the bond (Ceroni 2006). Alkali/aggressive environment, high temperatures during manufacturing phase, exposure to short wavelengths rays has adverse effect on the properties of the FRP material rebars. This has been discussed as follows:

### 2.3.1 Moisture exposure

Moisture can infiltrate the resin matrix and alter the FRP bar's mechanical properties by interacting at the resin-fiber interface. It can also result in swelling of FRP bars and tensile strength degradation of the bars. The effect is worsened if chloride ions are also contained in the moisture, as with marine environments (Ceroni 2006).

### 2.3.2 Alkali exposure

Concrete is an alkaline media with a pH ranging from 13 to 14. FRP material reacts with alkaline solutions that result in strength degradation. Resin protection is required with GFRP bars (Benmokrane, Mohamed, and Cousin 2020). Polyester resin and Vinyl ester resin are two of the resin material types used to provide alkali resistance to GFRP bars. Carbon fibers, as opposed to FRP fibers, do not experience deterioration in aggressive environments, as they are resistant to alkali, acids, and organic solvents.

### 2.3.3 High temperatures

Temperature changes affect the FRP bars. At elevated temperatures, massive strength degradation occurs in FRP bars. Besides this, as mentioned earlier, the FRP bars have two different values of thermal expansion coefficient in the transverse and longitudinal directions, which can cause compatibility issues between concrete and reinforcement as both experience thermal changes.

### 2.3.4 Ultraviolet radiation

Ultraviolet radiation also affects the performance of the FRP-concrete bond. Great care is required for the storage of FRP bars before using them for construction. A tensile strength reduction of 13% for AFRP bars after 2500 hours of exposure has been reported. For GFRP bars, the reported strength reduction is 8% after 500 hours of exposure (Ceroni 2006).

## 2.4 Bond strength of FRP to concrete

The FRP bar-concrete bond has been analyzed in a lot of studies. (Benmokrane 2000) studied the bond of GFRP bars with varying diameters (19.1 mm, 15.9 mm, and 12.7 mm), and different surfaces (sand-coated and smooth). Normal strength concrete cylinders were used. The lengths of embedment used were $5d_b$ and $10d_b$ (Where $d_b$ is the bar diameter). Results showed that for longer embedment length, concrete split failure occurred, and for shorter embedment length, pull-out failure was observed. The bond strength values ranged from 11.1 to 15.1 MPa with 12.9 MPa as the overall average. Compared to deformed steel bars, the GFRP bars bond strength came out to be an equivalent of 73% of steel bars bond strength. The bond strength of steel bars was also studied in the same study.

(Tang, Lo, and Balendran 2008) analyzed the bond strength by using three different FRP bar types: Glass Vinyl-Ester, Carbon-Epoxy, and Carbon Vinyl-Ester. The bars were embedded in concrete cubes of 150 mm sides. The bar diameter and embedment length used were 12.7 mm and $5d_b$, respectively. All the bar types were observed to have a similar bond-slip pattern, which led to the conclusion that the bond strength was influenced by the resin type.

(Tang et al. 2008) studied the effects of varying the surface treatment, embedded length, and shape of GFRP bars on the bond strength with concrete. The sand-coated, smooth circular and smooth elliptical GFRP bars were tested in the study. All sand-coated bar samples experienced concrete split failure. With sand coated GFRP bars, the average bond strength values were the highest. Test samples with shorter embedment lengths experienced greater bond stress as the bond perimeter reduced.

(Tang et al. 2008) carried out pull-out tests on 88 samples of CFRP and GFRP bars to study their bond strength. Different surface types and bar diameters were used while keeping the embedment length constant at $5d_b$. The bar diameter values used were 8, 12, 16, and 19 millimeters. The concrete strength range was 28-52 MPa. With the increase in the compressive strength of concrete, the value of the bond strength also increased along with a change in failure mode. Especially with higher concrete strength, the larger diameter bars exhibited lower bond strength. Also, for the same load values, GFRP bars experienced greater slippage than CFRP bars. In the GFRP helical wrapping bar, the surface exhibited greater bond strength. For CFRP sand-coated bars, the bar exhibited greater bond strength.

(Harajli and Abouniaj 2010) studied the effects of several factors, namely: surface treatment, type of FRP bar (ribbed and thread wrapped), and transverse steel confinement. He studied the GFRP bar's splice length in tension. Local bond stress-slip and splice bond strength response was studied using reinforced concrete (RC) beams and pull-out test specimens, respectively. The RC beams were designed with three different values of development length: $15d_b$, $20d_b$, and $30d_b$, and at the mid-span, two overlapping bars were provided. To study the bond strength with the effect of the surface treatment, ribbed and thread-wrapped bars were used. With the help of 8 mm U-shaped stirrups, equally spaced, the effect of the transverse steel confinement effect in the overlapping zone was studied. For comparison, reinforced concrete beams with regular steel bars were also tested. With pull-out tests, GFRP bars with an embedment length of $7d_b$ were placed in the middle of concrete cubes. The bonded length resulted in a $c/\ d_b$ ratio of 5.75. It was observed that all RC beam samples reinforced with steel bars or GFRP ribbed bars failed in a concrete split failure. Conversely, the gradual pull-out bond failure was observed in the reinforced concrete beams reinforced with bars thread wrapped. One reason for this behavior is that the ribbed GFRP bars form a mechanical bond with the concrete because of the surface deformations that result in better slip resistance. With ribbed GFRP bars, the bond stress-slip behavior resembled closely to the deformed bars of steel. In the GFRP bars, the bond stress was increased by 15-30% when transverse reinforcement was used.

(Chang et al. 2010) performed a numerical analysis on the pull-out behavior of FRP bars with different embedment lengths and diameters of the bar. Finite element modeling was carried out on the pull-out samples to analyze the damage models. A four-node meshed isometric element was used to simulate the plane stress. To simulate the real bond, a 2D four-node element with a single layer isometric element was used. In the lateral direction, displacement was induced on the loaded end of the bar, and concrete was restrained at the right side. 150 mm concrete cubes were considered with different embedment length (25, 60, 70, 80mm), and bar diameter (10, 15, 20mm) values. Tests showed that with the increase in the embedment length of the FRP bar, the value of the load also increased. The bond strength with the variation in FRP bar diameter didn't affect it.

Throughout the previous few decades, Glass Fiber-Reinforced Polymer (GFRP) bars have been examined, and accordingly have been observed they have benefits over steel. Even with these benefits, the utilization of GFRP bars was up to this point restricted because of a founding resilience issue for a portion of their mechanical properties. Therefore, FRP bars made of basalt (BFRP) were as of late presented in the development field as the option of regular GFRP bars. Altogether, for FRP bars to be broadly carried out in concrete structures, the study of their bond performance ought to be completely examined.

## 2.5 Production of BFRP bar

Basalt fibers famed in recent years thought the construction industry, out of all type of fibers, due to its high strength as compared to weight ratio. It is 3 to 4 times light as steel and 2 to 3 times more strength than steel.

Paul Dhe (from Paris, France) was the first research who understand the manufacturing phenomenon of Basalt Fibers. A special furnace was assembled/made for the manufacturing of Basalt fibers (DHE 1923) Colombo et al., 2012). Its high manufacturing cost renders its applications as common as GFRP material which needs attention, to reduce its manufacturing cost and to make it useful. Due to high manufacturing cost, US FRP manufactures abandoned for producing Basalt Fibers (Faruk, Tjong, and Sain 2017) whereas GFRP based material is commercialized more in Ohio (SLAYTER 1938). USSR has database basalt fibers vide various tests for safety which using ballistic missile type applications (Jamshaid and Mishra 2016). USSR (Zych and Krasodomskr 2012) banned Basalt Fiber in early 90s but later, soon in mid of 90s, FRP material was declared safe and useful for public use which resulted in uprise of the material around the world as it is taken up by big businesspersons and manufacturers especially the ones that are aligned in Soviet. By today, basalt has become the most popular FRP material use as reinforcement to replace steel due its very high strength. In resilience/electromagnetic transparency type constructions.

Liquid stone material underneath the earth's surface is called magma and, a short time later, called magma when it shows up at the earth's surface. Liquid rocks should be separated from plutonic rocks (they are coarse-grained and hardens deep inside the surface of the earth), and are mostly gathered by their mineralogical course of action, or volcanic pumice (these are fine-grained and set closer to the surface and hardens quickly), as requested (Myron G. Best 2002).

The most widely recognized volcanic stone is Basalt, and rocks having enormous quantities of basalt (gabbro, diabase, and their transformed reciprocals) are the Earth's most prominent in the crust. A coarse-grained plutonic rock, Gabbro set inside the Earth's outer layer. Diabase is constitutionally comparable to gabbro and basalt. However, for actual design, it assembles into basalt and gabbro when crystallizes rapidly and slowly, respectively (Zych and Krasodomskr 2012).

The compound definition contains over 45% and under 52% of SiO2 and five percent of absolute alkalis (K2O + Na2O). High-strength strands are guaranteed by using high silica and low iron substances. When meeting the precondition for the substance arrangement, any mentioned unrefined components can be used for its production, as directed by various public records. Russian details for basalt fiber are characterized as softened basalt or gabbro-diabase (ISC 2014). Following

Figure 2. 1 shows the explanation of the hotspot for the creation of these fibers. The following section shows the assembling a system of strands.

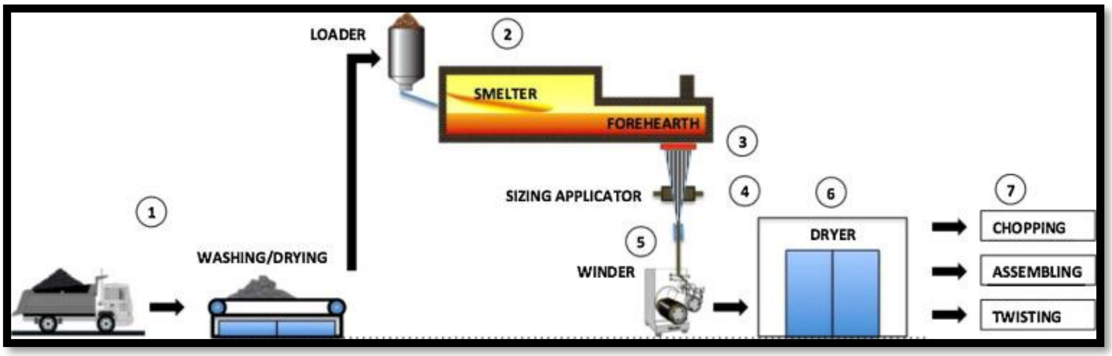


**Figure 2. 1 BFRP bar Production Process**

The leftward half of the figure shows that the crude stone is first squashed, washed, and afterward shipped to a furnace. A temperature of 1450°C (2640°F) is required for dissolving a base in the liquefying system. The hazy basalt absorbs the infrared portion, because of this, it is more difficult than glass to have a uniform temperature. Placing a

Liquid basalt in the smelter for stretched-out timeframes guarantees a uniform temperature. After liquefying occurs and consistency is achieved by expelling gases, the liquid is collected within the front hearth (Ipbüker et al. 2015). Using a platinum/rhodium pot bushing having 9 to 24 micrometer spouts, the liquid material is constrained to expel consistent strands. During the assembling system, basalt fibers are measured to ensure the fiber and to give the pitch similarity required for ideal execution. Estimating like hushes, starch, gelatin, oil, or wax applies to work on the bond and to limit debasement of filament strength that would somehow or another be made by fiber scraped area ((Saman Bagherpour 2012)(Zych and Krasodomskr 2012) The filaments can be made as slashed fibers or nonstop strands roving's (Fiore et al. 2015). After the production of these fibers, their structure can be changed over into an appropriate structure for every specific application (Dmitri Pavlovski 2007).

Just crude basalt is important to deliver the fibers, and the level of contamination of the natural substance for the filaments relies just upon the stone source. As an outcome of explicit sorts of unique stone sources, over one class of basalt strands with various compound pieces might be gained. Because of these variables, basalt filaments might have several various mechanical or actual characteristics (Zych and Krasodomskr, 2012). During the creation cycle, no extra substance parts are expected to deliver basalt strands. Green as compared to glass, poisonous fixings, normally used in glass plan, can be prevented (Zych and Krasodomskr 2012). Production of glass filaments necessities the expansion of a few fixings and a monotonous blending procedure.

Figure 2. 2 Basalt FRP bar Manufacturing Steps

Fibers are known for their high-elasticity to-weight proportion and explicitly when the rebar formed for consumption opposition when contrasted with carbon-steel support. The fiber volume is liable for the rigidity of the FRP rebar. As per the ASTM D2584 \Standard Test Method for Ignition Loss of Cured Reinforced Resins," the fiber content will not be under 55% by volume or 70% by mass and will be accounted for by volume or by mass as per the technique used (ASTM 2011).

A volume part of around 80% is normal for FRP rebar's, and as per (Bagherpour, Bagheri, and Saatchi 2009), a fiber content past that doesn't permit the fibers to be encircled by the gum grid. The ductile conduct of the FRP rebar is portrayed by a direct versatile pressure strain relationship up to failure of the bar, as displayed in Figure 2. 3.

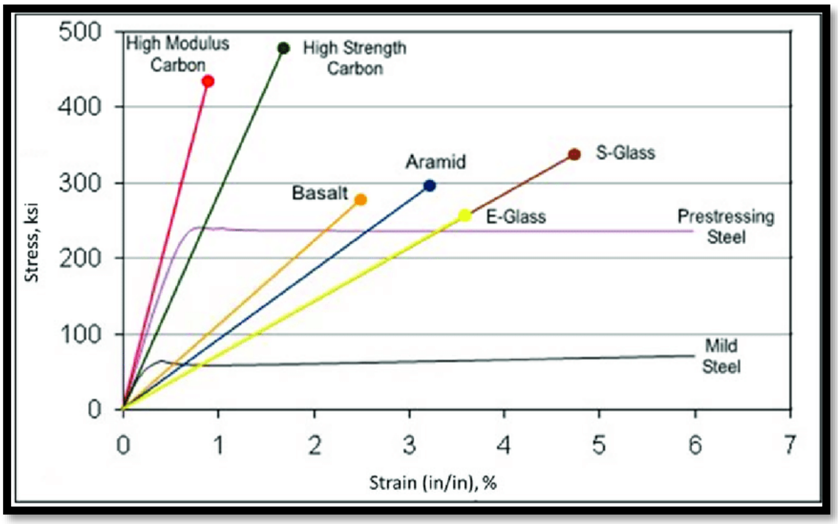


Figure 2. 3 Tensile Properties of different FRP Bars

The chart shows the stress-strain outlines for various FRP composites contrasted with the stress-strain behavior for steel. It very well may be seen that the grade of the FRP items is more modest than the one for steel, yet the place of most extreme ductile pressure is higher for all FRP items. The greatest grade and most noteworthy tensile strength with the least strain is reached via carbon FRP trailed by aramid FRP, which has a higher strain than basalt FRP. Glass FRP can be brought up as the FPR item with the least tensile stress and most reduced elastic strain modulus and basalt FRP is arranged among aramid and glass. Contrasted with steel rebars, basalt FRP rebars lower higher rigidity yet lower extreme tensile strain and lower tensile modulus of flexibility, which brings about a weaker fracture for FRP items. The modulus of elasticity of the FRP rebar, in contrast to steel, changes with the increases in its diameter, while the longitudinal modulus doesn't change the shear lag impact turns out to be more critical as the bar width increments because the center of the bar is additionally separated from the external surface and more resin should be started. This prompts lower strength estimations for bigger distance across rebars on the surface that the internal center doesn't contribute totally to the stresses conveying system before the furthest fibers come up short. The tensile strain in the furthest fiber arrives at its breaking point before the deepest fibers. The justification for the longitudinal modulus to remain steady is thought to be a consequence of the estimation strategy, in which an extensometer is applied at the furthest surface of the fiber that is enacted to its maximum capacity | autonomous of the rebar distance across.

## 2.6 Concrete Elements Reinforced with BFRP

BFRP based rebars are most reasonable to replace the steel, epoxy or treated steel (Luca and Zadeh 2019). Failure modes of FRP reinforced bars are vital for designing purposes (Ehrenstein, 2006). Steel has three phases until failure. FRP based rebars, do not show yielding in first two phases and fails in third phases without any warning (ACI Committee 440 2007).

Concrete pH is 13, when it subjects to environmental conditions (deicing salts etc.) it alkalinity decreases. When pH of concrete reduces below 9, steel start oxidizing causing corrosion. Corrosion of steel reduces its tensile strength which dead its purpose and functionality (ACI Committee 440 2015).

Due to corrosion resistive nature of FRPs, it finds its applications in structures like bridge decks, roads, which subject to severe environmental conditions like saline water, alkaline, deicing, etc. (Brik 2003).

Use of FRPs as reinforcement has become common around the world. Composite Member with FRPs rebars have bending moments are as per AI 440.1 R-06 which are comparable to intrinsic properties (Patnaik 2009). FRP is restricted as material for the manufacturing of pressure sections and zones where 2nd re-allocation is obvious, due to its non-yielding property (Luca and Zadeh 2019).

FRP material is tested under SEM analysis at high temperature for 100 hours which depicts anti-critical situation of debasement whereas peripheral layer was damaged due to molding. For around 3000 hours in antacid, crossover and flat between shear strength was reduced due to molding. Similarly, flexure strength was also reduced due to molding in primary setup when placed for 3000 hours. More tests are required for databasing and standardizing the properties of FRP as different FRP material are present with varying properties. (Elsafty et al. 2014).

Near solidness factors, ecological effects of the BFRP bar creation must diminish contamination. Because of the elevated temperature needed for creation, steel support has a higher carbon impression than FRP support. Reusing isn't as natural as duplicating steel. Without consumption, the existing cycle costs related to FRP-built-up structures are logically lower where steel erosion ought to be a worry. An examination between FRP-built up asphalt and steel-supported asphalt over still up in the air showed that FRP support had an altogether more modest ecological effect than the variant with steel (ACI Committee 440, 2015).

Flexure behavior and durability of Basalt Fibers is focused in research of (Sim, Park, and Moon 2005) and they found, GFRP and BFRP materials shows similar behavior over long span as both are the FRP based products. In aggressive environment like alkali solution exposure, both BFRP and GFRP fibers loses their ultimate strength and also loses the volumetric stability as compared with CFRP fibers. When exposed to narrow bandwidth wavelengths (X-rays/Ultraviolets etc.) strength reduction is more in GFRP and BFRP fibers than in CFRP fibers whereas BFRP has 50% of GFRP strength reduction ratio but they behave reverse with respect to thermal stability. BFRP maintains 90% strength than GFRP fibers when subject to thermal changes. (Brik 2003) compared properties of basalt fibers and basalt reinforcement in his research and he concluded that modified BFRP fibers has high ultimate moment capacity than first crack moment. As all beams were collapse under flexure therefore, BFRP based reinforcement can be used as steel replacement. This case has also been addressed in (ACI Committee 440 2006).

A large-scale pull-out test experiments were performed (Adhikari 2009) over BFRP reinforcement for understanding the bond behavior of BFRP with concrete. Each specimen had 10 inches of embedded length of BFRP bars. Unfortunately, the results obtained had large deviation from each other which seems quite unpredictable about BFRP behavior. Therefore, more research was suggested to carry to understand the behavior of BFRP rebars.

The principal necessity for accomplishing the required behavior is that steel or FRP support should bond impeccably with the concrete. There will not be any slippage of steel or Basalt FRP bar up to the concrete failure. The utilization of high-strength material is useless if there is no composite action between the concrete and reinforcing bar. For instance, if the tensile load taking capacity of the reinforcement bars isn't fully used by the structural components when they apply to the external loading, their failure will be brittle in nature. So, it is an important parameter to know about the bond performance between the concrete and FRP bars to use the FRP as the reinforcing bars in the structural elements of a structure.

For the incorporation of FRB rebar’s in concrete matrix, bond properties are important to configure. Splice length of rebar, development length and concrete cover etc. depends on bond slip of the rebar. Therefore, for the service life of a structural member with incorporation of FRP reinforcement, durability of bond has vital importance. Applied load, Concrete Matrix Strength, Modulus of Elasticity, Re-bar placement, FRP reinforcement material type, FRP rebar material properties are key features for defining the bond performance of FRP rebar with Concrete. Deformed and smooth shape of FRP rebars also effect the bond strength. Due to dependence on various factors, bond stress/capacity is unpredictable.

Bond strength varies with compressive strength of concrete when it is ranges between 30 to 40 MPa. Due to which failure of member is obvious on FRP rebar surface instead on the concrete. This might be due to the brittle behavior of the FRP material. Therefore, (Tepfers 2004) and (Achillides 1998) suggested bond strength as independent of the concrete strength.

FRP rebar strength depends on the type of fiber by which it is made which ultimately develop rebar capacity/strength. FRP materials are brittle in nature due to which by increasing bar diameter size, ultimate strength of bar will be decreasing. This adverse relation is due to its low shear strength in longitudinal direction. Stress distribution in FRP material rebar from core to the periphery fibers is nonlinear as observed in the tensile testing of the FRP rebars. Nonlinear distribution of the stresses compromises the bond strength for which shear lag factor is completely responsible. This is now the clear justification that why bond strength of different size diameter FRP rebars is different.

(Tepfers 2004) mentioned that when FRP bars are used for tests, it is important to show who has delivered and when the bar has been produced. He closed each kind of FRP bar must be tried to gain its specific bond coefficients in the recent studies on the FRP bars. Bar size is normalized in ACI 440.1R (2006).

(Harajli and Abouniaj 2010) expressed that the outer layer of the FRP bars is more fragile and gentler than steel bars which results in the fracture of the outermost layer of the FRP bar rather than the concrete, especially in high strength concretes. In this manner, the ribbed FRP bars are good than the spirally wrapped FRP bars. The ribbed bars displayed in their review are not the same as the ribbed bars displayed in (ACI Committee 440 2006). FRP bar bond strength can be better by adding sand covering.

Another research by (Brik 2003) was concluded about BFRP bars which used the ASTM 234 Rev A for its bond strength. In this regard, Pullout tests were performed and in his initial outcomes he found no bond between the concrete and BFRP rebar as the bar was slipping without any significant friction. Later, the bars were re-adjusted and tested and this time he found the resistance against slipping of BFRP rebar in concrete matrix. This deviation of results again makes BFRP unpredictable for its properties and needed broad research to understand the effects. Due to its unpredictable nature, it has less attraction in market. His research included six samples each containing 19mm bar and research was remained unpredictable for the bond behavior of BFRP rebars.

Similarly another attempt by (Adhikari 2009) was performed in Blast Fiber Reinforced Bars to understand the bond strength using Pullout Test. His research used various diameter rebars which also given quiet deviated results and spotted light for more research on BFRP rebars for its bond strength behavior.

## 2.7 Study on geopolymer concrete

The ecosystem is being polluted by carbon dioxide generated worldwide, and in the last several decades, levels have increased to the point that the environment is experiencing great harm, such as climate change. The manufacturing of cement accounts for 7% of all carbon dioxide generated globally (Benhelal et al. 2013). Additionally, it has been proposed that treating concrete manufacturing facilities is one method of reducing CO2 generation. Approximately 1 ton of atmospheric co2 is emitted into the atmosphere for every 1 ton of Portland cement produced, according to studies (Malhotra 2010). Researchers attempted to substitute a portion of OPC with another cementitious substance several decades ago to reduce the consumption of Portland cement. In addition to silica fume and rice husk ash, fly ash and ground granulated blast furnace slag have also been exploited. It has been demonstrated that better concrete with more strength than standard concrete may be produced by partially replacing slag with cement (Malipeddi and Adiseshu 2021). A byproduct of the steel and iron sector is slag. Slag is a substance that is naturally reactive, but when it reacts with water, certain hydration products have created that coat the outer surface of slag with a film and prevent further reaction. However, when portlandite, a result of the cement's hydration process, is combined with slag, it reacts to form chemicals that increase the strength. Slag is utilized by some types of cement; therefore, this reaction occurs when slag is also employed. In a similar vein, fly ash has also been utilized in concrete as a partial substitute for cement in various doses, with the conclusion that the early strength was reduced but retrieved at later phases by curing and permanence attributes were also enhanced (Rashad 2015). Fly ash's hydration reaction occurs slowly, which accounts for why it develops strength more slowly than slag. Additionally, silica fume has been utilized in place of cement to lessen carbon footprints, with good results. Concrete's porosity is decreased by silica fume, which enhances the material's durability. The portlandite that is created because of Portland cement hydration is consumed by silica fume. Additionally, durability problems including alkali-aggregate interactions and sulfate assaults are greatly influenced by Portlandite, also termed calcium hydroxide. The strength is increased by adding silica fume because portlandite reacts with the fume to create the C-S-H gel. According to the study, silica fume and gypsum can decrease the quantity of cement needed to produce concrete while increasing its strength by substituting OPC by 36%. (Campos et al. 2020). Another research demonstrates that Portland cement may replace cement that contains silica fume and volcanic ash in concrete without affecting its durability (Kupwade-patil et al. 2018). The durability of conventional concrete can be greatly enhanced by the addition of fine, spherical silica fume particles. The agricultural sector, which is abundant in alumina and silica, produces rice husk ash as a byproduct. Rich husk ash also makes the C-S-H gel by devouring the portlandite, increasing the strength of the concrete. Additionally, the research has demonstrated that employing 15% rice husk may thicken the concrete matrix, providing notable resistance to sulfate intrusion (Hu, He, and Zhang 2020). None of the existing techniques succeeded in completely replacing Portland cement with another cementitious material; they were all utilized to lower the usage of Portland cement. To create the inorganic polymers known as the geopolymer, material rich in aluminates and silicates combines with alkalis from alkali activators to form geopolymer concrete. Alkali activators react with materials that are high in aluminosilicate and silicate oxides to form 3D polymerized chains as a byproduct. Like how C-S-H gel is created in OPC concrete, A-S-H gel, which is what gives concrete its strength, is created in geopolymer concrete because of alkali activation.

Geopolymer concrete has variables that needed to be studied. Using a type of cementitious materials plays a key role in unique characteristics of alkali-activated concrete. Alkali activated concrete using slag, fly ash geopolymer, metakaolin-based geopolymer, and rice husk-based geopolymer concrete are some of the few examples of cementitious material that can be used for geopolymer concrete. The basic difference between conventional concrete and geopolymer concrete is the replacement of cement and the use of alkali solution instead of water. Using the type of material and alkali solutions varies for every type of geopolymer concrete.

To minimize the negative aspects of OPC concrete, OPC cement is fully being replaced by combined of other green materials such as fly ash and ground granulated blast furnace slag. Because of the better durability properties of geopolymer concrete as compared to conventional OPC concrete, a recent trend to preferring geopolymer concrete over conventional concrete has been seen. As green concrete can future of the construction industry, the bond strength of reinforcement in this type of concrete should also be studied. Steel reinforcing bars in concrete tend to corrode with time as chloride ions and moisture breach into the concrete. Damage manifested by the corrosion of the steel bar is a very costly procedure. To avoid this degradation phenomenon of concrete because of corrosion of steel reinforcing, FRP bar is recommended as replacement of steel bars by several studies. Basalt Fiber-reinforced polymer bar is superior among other FRP bars, so its bond performance in geopolymer concrete is a particularly important parameter to be studied.

# RESEARCH METHODOLOGY

The following chapter includes a detailed study of the material properties, specimen configuration, and test setup.

## 3.1 Basalt fiber reinforced polymer bars

Basalt FRP bar was procured from Hengshui Aoliadne trading Co. Ltd. (Hengshui city, China). BFRP bars are manufactured by the pultrusion method by joining the thin basalt fibers and resin matrix, to get the polymeric matrix. E-Glass and polyester were used as a resin matrix to manufacture the basalt FRP bars. BFRP properties are shown in Table 3. 1.

**Table 3. 1 BFRP bar properties**

| **Parameters** | **Diameter of the bar (mm)** | | |
|---|---|---|---|
| | 12.7 | 15.9 | 19 |
| **Tensile Load (kN)** | 97 | 130 | 225 |
| **Effective cross section (mm$^2$)** | 113 | 185 | 289 |
| **Tensile strength in core (MPa)** | 799 | 703 | 779 |
| **Tensile E modulus (MPa)** | >45000 | | |
| **Double Shear Strength (MPa)** | 150 | | |

## 3.2 Types of Concrete

For this research, different types of concrete were used to evaluate the bond performance of the concrete. Following are the types of concretes that were used:

- The normal strength of concrete.
- The high strength of concrete.
- Geopolymer concrete.

A concrete mix of compressive strength 25 MPa was prepared with normal strength concrete and geopolymer concrete. The high strength of 60 MPa was also used in this research. To study the bond performance of basalt FRP bar, three different kinds of concrete were used in this research. Following Table 3. 2 shows the mix proportions of normal strength concrete and Table 3. 3 shows the mix proportions of high strength concrete used in this study.

**Table 3. 2 Normal strength concrete mix design**

| **Mix constituents** | **Quantity (Kg/m$^3$)** |
|---|---|
| Cement | 445 |
| Sand | 750 |
| Coarse Aggregate | 1060 |
| Water | 195 |

**Table 3. 3 High Strength Concrete Mix Design**

| **Mix Constituents** | **Quantity (Kg/m$^3$)** |
|---|---|
| Cement | 635 |
| Sand | 860 |
| Aggregate | 1020 |
| Water | 185.31 |
| Silica Fume | 63 |
| HRWRA | 6.4 |

The water to cement ratio was kept minimum in high strength concrete mix design to get the higher strength. To increase the workability of the concrete high range water reducing agent named Chemorite was used. Following Table 3. 4 shows the mix constitutes of geopolymer concrete used in the research.

**Table 3. 4 Geopolymer Concrete Mix Design**

| **Mix constituents** | **Quantity (Kg/m$^3$)** |
|---|---|
| Fly Ash | 318 |
| GGBFS | 79 |
| Sand | 645 |
| Aggregate | 1205 |
| Sodium Hydroxide | 40 |
| Sodium Silicate | 104 |

Contrasted with traditional concrete made by hydrating Portland cement, geopolymer concrete is a contemporary invention. Materials high in aluminate and silicate oxides are utilized in geopolymer concrete to replace cement in the mix. The sort of cementitious material employed in geopolymer concrete affects the strength gain of the material as well. For the creation of geopolymer concrete, Class F fly ash and GGBFS are chosen as cementitious ingredients. The coal industry produces fly ash as a byproduct. In comparison to slag, fly ash develops strength more slowly. A waste of the steel industry is ground, granulated blast furnace slag. The actual quantity of cementitious material employed is 80 percent fly ash and 20 percent slag, respectively. In geopolymer concrete, the cementitious ingredient is activated using alkali activators. In this work, sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) are employed as activators. Fly ash has a lower probability of reactivity, hence activating it requires a large amount of sodium hydroxide. In this study, fly ash and slag activation is carried out using a 10-molar sodium hydroxide solution. Because of how intensely sodium hydroxide reacts with slag, even very little concentrations of the compound can activate it. Fly ash makes up most cementitious materials, hence the overall behavior design mix reflected the characteristics of fly ash.

. Slag is very reactive to sodium hydroxide and can be activated by using extremely low molarity of sodium hydroxide. Since most cementitious material is composed of fly ash so, the overall behavior design mix was like properties associated with the fly ash. Sodium hydroxide in form of flakes and specific gravity of 2.13 g/cm$^3$ is used. Sodium hydroxide is also responsible for high early strength and because of the low activity of fly ash, high molarity of NaOH is used. Sodium silicate is purchased in form of a solution. Sodium silicate handles ultimate strength in the geopolymer concrete. A solution of sodium silicate is thick in nature, so it is especially important to use the optimum amount of sodium silicate, otherwise workability of the geopolymer mix can be reduced significantly. Sodium hydroxide to sodium silicate ratio of 2.5 was selected in this study to produce concrete. Sodium hydroxide flakes were dissolved in a water tap for 24h before mixing to get the desired molarity. Sodium silicate and sodium hydroxide can also be mixed 24h before use.

## 3.3 Specimen preparations

The bond performance of the Basalt FRP bar was checked with different bar diameters (12.7, 15.9, and 19mm) and with different embedment lengths (5db, 10db, and 15db where db is a bar diameter of BFRP bars). To ensure the desired bond length bar was covered with duct tape so there was no contact with the concrete and bar. A total number of 162 samples were prepared for the pull-out test. Following Figure 3. 1 shows the BFRP bar arrangement in the concrete.

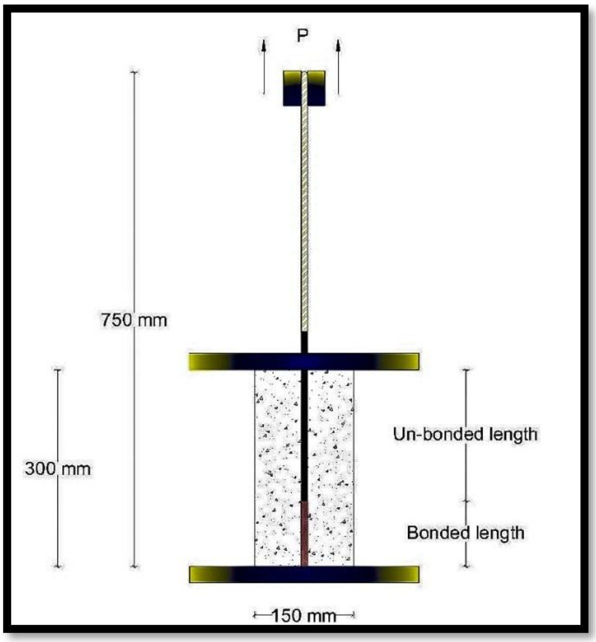


**Figure 3. 1 BFRP Bond Condition**

Concrete cylinders of 150 x 300 mm were used to study the bond performance. Conventional concrete specimens were cured in the tap water for 28-days. After that, these specimens were taken out for the pull-out test. With geopolymer concrete, prepared specimens were cured in the ambient condition for 28-days.

## 3.4 Pullout test

Corrosion of the reinforcement bar is one of the key phenomena in the degradation of bars. It reduces the serviceability of the RC structures. A considerable amount of money is required for its repair and retrofitting to the damaged part of the RC structure. When the conventional steel bar is used in an aggressive environment, it tends to corrode and reduce its cross-sectional area and its strength. Since the bond performance of the concrete depends upon both reinforcing bars and concrete, it reduces as the steel bars get corroded. The pullout test is one of the simplest tests to check the bond performance of concrete and reinforcing bars. During the pullout test bar, a static tensile force is applied to the reinforcing bar at a constant rate of 2.5 KN/s. Concrete specimens were placed inside the two steel plates of thickness 30 mm and four steel rods were used to hold the whole assembly together, as shown in

Figure 3. 2.

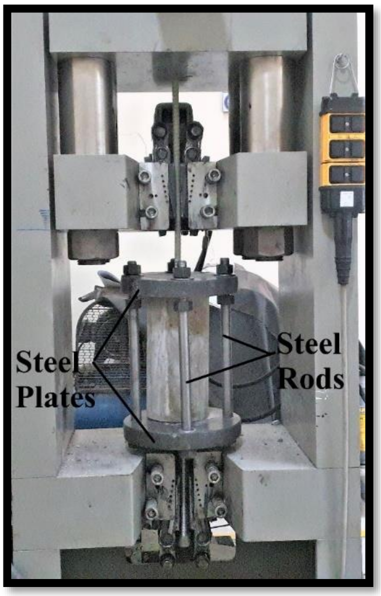


**Figure 3. 2 Universal Testing Machine**

Bond strength is calculated by the following equation:

$$\boldsymbol{t_{max.}} = \boldsymbol{P_{max.}} / \boldsymbol{\pi d l_d} \qquad \textbf{Equation 1}$$

Were

$P_{max}$ is the maximum tensile load applied by the UTM machine.

d is the bar diameter.

$L_d$ is the development length.

## 3.5 Selected Environments

As explained in the literature, the performance of the FRP bars is degraded in aggressive environments such as seawater and alkaline solution. To fully understand the behavior of BFRP bars, both alkaline and seawater were selected.

### 3.5.1 Marine Environment

Conventionally used reinforcement bars tend to corrode in the marine environment. Since concrete is a porous material with time, it deteriorates, and all the aggressive media gets the chance to get inside the concrete structure and damages the reinforcement bar. So, in this research marine environment was selected to check its bond performance. Curing of concrete specimen in seawater shown in Figure 3. 3.

Seawater was prepared according to the ASTM standard D1141-98 (ASTM 2021a). The composition of sea water was NaCl of 24.53g + $MgCl_2$ of 5.20g + $Na_2SO_4$ of 4.09g

+ $CaCl_2$ of 1.16g + KCl of 0.695g + $NaHCO_3$ of 0.201g + KBr of 0.101g + $H_3BO_3$ of 0.0207g + $SrCl_2$ of 0.0205g and NaF of 0.003g in 1L of water.

**Figure 3. 3 Curing of Concrete Cylinders in Seawater**

### 3.5.2 Alkaline Solution

As explained earlier, the performance of FRP bars decreases conveniently in alkaline environments. That is why the alkaline environment was also used. The alkaline solution was made according to the ASTM standard D7705/D7705M (ASTM 2021b).

Curing of concrete specimen in alkaline solution shown in Figure 3. 4

PH of the solution was around 12 to 13, as per ASTM standard recommended. An alkaline solution of pH 13~14 was prepared according to the ASTM standard. Its composition was Ca (OH) of 115.5g + KOH of 4.2g and NaOH of 0.9g in 1L of water.

**Figure 3. 4 Curing of Concrete Cylinders in Alkaline Solution**

# RESULTS AND DISCUSSIONS

## 4.1 Introduction

This chapter discusses the outcomes of specimens both of which were conditioned and unconditioned and made of various types of concrete. The comparison of various harsh settings and concrete kinds is covered in depth.

## 4.2 Normal Strength Concrete

The pull-out test was performed to examine the bond strength of basalt FRP bar after 28 days of curing normal strength specimens. 18 specimens of normal strength concrete were examined in each environment using the direct pull-out test. With different bond lengths of 5db, 10db, and 15db, and varying the bar diameters of 12.7mm, 15.9mm, and 19mm were employed.

### 4.2.1 Unconditioned Specimens

The findings of the pull-out tests conducted on specimens of conventional concrete immersed in tap water are displayed in Table 4. 1.

**Table 4. 1 Pull-out Results of Normal Strength Concrete in Controlled Environments**

| Specimen | Time months | Peak Load KN | $ʈ_{max}$ MPa | Avg. $ʈ_{max}$ MPa | Failure Mode | Slip mm | Residual ʈ MPa |
|---|---|---|---|---|---|---|---|
| B 12.7-5db | 1 | 53.4 | 21.09 | 20.99 | P | 1.1 | 8.5 |
| | | 52.9 | 20.89 | | P | 1.15 | 7.1 |
| B 12.7-10db | -- | 56.5 | 11.16 | 11.05 | P | 1.3 | 4.9 |
| | | 55.4 | 10.94 | | P | 1.1 | 3.1 |
| B 12.7-15db | -- | 59.2 | 7.79 | 7.85 | S | - | - |
| | | 60.1 | 7.91 | | S | - | - |
| B 15.9-5db | -- | 72.5 | 18.27 | 18.30 | S | - | - |
| | | 72.8 | 18.34 | | S | - | - |
| B 15.9-10db | -- | 78.7 | 9.91 | 9.83 | S | - | - |
| | | 77.4 | 9.75 | | S | - | - |
| B 15.9-15db | -- | 82.4 | 6.92 | 6.89 | S | - | - |
| | | 81.6 | 6.85 | | S | - | - |
| B 19-5db | -- | 89.5 | 15.79 | 15.76 | S | - | - |
| | | 89.1 | 15.72 | | S | - | - |
| B 19-10db | -- | 96.2 | 8.49 | 8.46 | S | - | - |
| | | 95.7 | 8.44 | | S | - | - |
| B 19-15db | -- | 98.1 | 5.77 | 5.75 | S | - | - |
| | | 97.4 | 5.73 | | S | - | - |

***Note:*** ʈ = bond strength; P = pull-out; $S_{max.}$ = maximum slip; S = concrete split failure

### 4.2.2 Conditioned Specimens

Table 4. 2 and Table 4. 3 below demonstrate the behavior of the bond stress of concrete specimens of normal strength that were immersed in seawater and an alkaline solution for three months.

**Table 4. 2 Pull-out Results of Normal Strength Concrete in Seawater**

| Specimen | Environment | Time months | Peak Load KN | $\tau_{max}$ MPa | Avg. $\tau_{max}$ MPa | Failure Mode | $S_{max.}$ mm | Retention (%) | Residual $\tau$ MPa |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | Sea | 3 | 41.6 | 16.43 | 16.35 | P | 1.37 | 77.89 | 6.2 |
| | | | 41.2 | 16.27 | | P | 0.9 | | 4.3 |
| B 12.7-10db | -- | -- | 43.2 | 8.53 | 8.62 | P | 1.5 | 78.02 | 2.6 |
| | | | 44.1 | 8.71 | | P | 0.8 | | 2.1 |
| B 12.7-15db | -- | -- | 48.1 | 6.33 | 6.27 | P | 1.3 | 79.88 | 3.2 |
| | | | 47.2 | 6.21 | | P | 1.2 | | 2.9 |
| B 15.9-5db | -- | -- | 54.2 | 13.66 | 13.77 | S | - | 75.22 | - |
| | | | 55.1 | 13.88 | | S | - | | - |
| B 15.9-10db | -- | -- | 59.3 | 7.47 | 7.54 | S | - | 76.68 | - |
| | | | 60.4 | 7.61 | | S | - | | - |
| B 15.9-15db | -- | -- | 63.2 | 5.31 | 5.35 | S | - | 77.68 | - |
| | | | 64.2 | 5.39 | | S | - | | - |
| B 19-5db | -- | -- | 68.6 | 12.10 | 12.15 | S | - | 77.10 | - |
| | | | 69.1 | 12.19 | | S | - | | - |
| B 19-10db | -- | -- | 71.5 | 6.31 | 6.37 | S | - | 75.25 | - |
| | | | 72.9 | 6.43 | | S | - | | - |
| B 19-15db | -- | -- | 77.5 | 4.56 | 4.58 | S | - | 79.59 | - |
| | | | 78.1 | 4.59 | | S | - | | - |

***Note:*** $\tau$ = bond strength; P = pull-out; $S_{max.}$ = maximum slip; S = Split failure of concrete

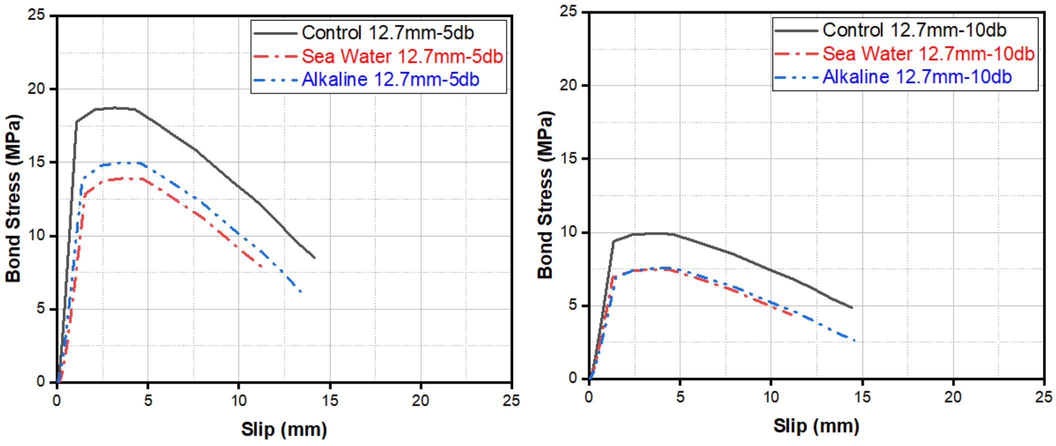
**Table 4. 3 Pull-out Results of Normal Strength Concrete in Alkaline Environment**

| Specimen | Environment | Time months | Peak Load KN | $\tau_{max}$ MPa | Avg. $\tau_{max}$ MPa | Failure Mode | $S_{max.}$ mm | Retention (%) | Residual $\tau$ MPa |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | A | 3 | 44.6 | 17.61 | 17.34 | P | 1.5 | 82.60 | 7.8 |
| | | | 43.2 | 17.06 | | P | 1.1 | | 2.7 |
| B 12.7-10db | -- | -- | 45.2 | 8.92 | 8.82 | P | 1.3 | 79.80 | 4.4 |
| | | | 44.1 | 8.71 | | P | 0.8 | | 3.9 |
| B 12.7-15db | -- | -- | 50.1 | 6.59 | 6.57 | S | - | 83.65 | - |
| | | | 49.7 | 6.54 | | S | - | | - |
| B 15.9-5db | -- | -- | 57.2 | 14.41 | 14.52 | S | - | 79.35 | - |
| | | | 58.1 | 14.64 | | S | - | | - |
| B 15.9-10db | -- | -- | 63.2 | 7.96 | 8.02 | S | - | 81.61 | - |
| | | | 64.2 | 8.09 | | S | - | | - |
| B 15.9-15db | -- | -- | 68.7 | 5.77 | 5.73 | S | - | 83.17 | - |
| | | | 67.7 | 5.69 | | S | - | | - |
| B 19-5db | -- | -- | 72.2 | 12.74 | 12.54 | S | - | 79.56 | - |
| | | | 69.9 | 12.33 | | S | - | | - |
| B 19-10db | -- | -- | 79.1 | 6.98 | 6.95 | S | - | 82.07 | - |
| | | | 78.4 | 6.92 | | S | - | | - |
| B 19-15db | -- | -- | 81.5 | 4.79 | 4.82 | S | - | 83.84 | - |
| | | | 82.4 | 4.85 | | S | - | | - |

***Note:*** $\tau$ = bond strength; P = pull-out; $S_{max.}$ = maximum slip; A = Alkaline Solution; S = Split failure of concrete

### *4.2.2.1 Bond Stress-Slip relationship*

Figure 4. 1 illustrates the connection between bond strength and slip. The graph shows that before achieving the maximum tension force, there was a minor increment in the slip value. A sharp decline in the tensile load and a rise in the slip value occurred in all specimens after achieving the maximum tensile load. A dial gauge was used to measure the continuous slip values. Slip value could not be captured in the event of concrete split collapse because UTM stopped abruptly.



a) b)

**Figure 4. 1 Relationship between Bond Stress and Slip a) 12.7mm-5db b) 12.7mm-10db**

### *4.2.2.2 Comparison against different environments*

The highest bond strength of concrete, 20.99 MPa, was achieved using normal strength. The maximum bond strength was evaluated after three months of immersion in an alkaline medium and seawater, respectively, and was found to be 17.34 MPa and 16.35 MPa. The relationship between bond length and bond strength in aggressive environments is shown in Figure 4. 2.

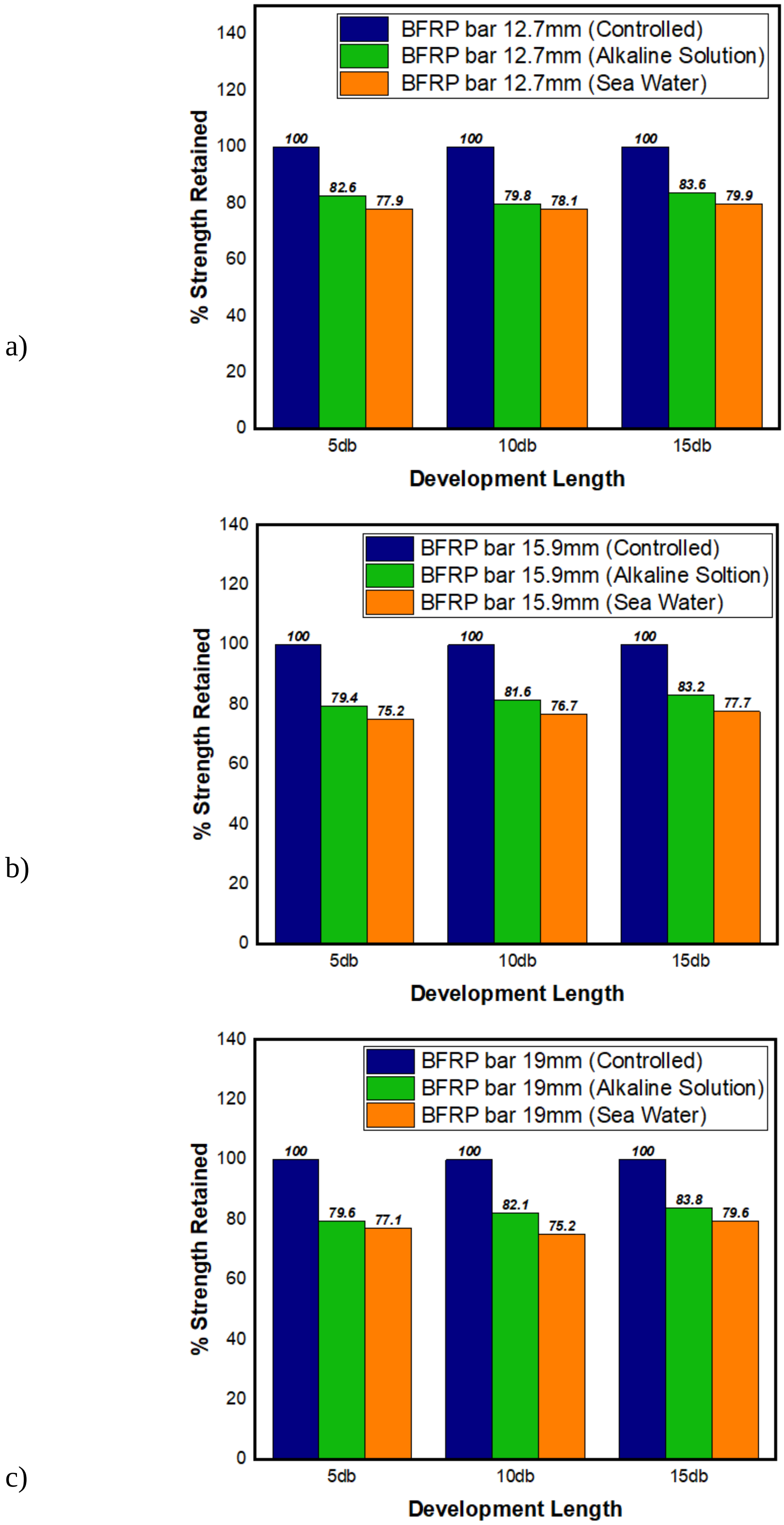


**Figure 4. 2 Relationship between % strength retention and development length in Normal Strength Concrete a) 12.7mm b) 15.9mm c) 19 mm**

## 4.3 High strength concrete

The bond strength between the BFRP bar and high-strength concrete was examined on 18 specimens in various environments.

### 4.3.1 Unconditioned Specimens

On 18 specimens in unconditioned situation, the bond strength between the BFRP bar and high-strength concrete was evaluated.

Table 4. 4 shows the pull-out results of high-strength concrete specimens.

**Table 4. 4 Pull-out Test Results of High Strength Concrete in Controlled Environment**

| Specimen | Time months | Peak Load KN | ţ$_{max}$ MPa | Avg. ţ$_{max}$ MPa | Failure Mode | Slip mm | Residual ţ MPa |
|---|---|---|---|---|---|---|---|
| B 12.7-5db | 1 | 57.1 | 22.5 | 22.45 | P | 1.21 | 4.6 |
| | | 56.8 | 22.4 | | P | 1.01 | 5.9 |
| B 12.7-10db | -- | 60.4 | 11.9 | 12.0 | B | 1.45 | B |
| | | 61.1 | 12.06 | | B | 0.75 | B |
| B 12.7-15db | -- | 61.5 | 8.1 | 9.1 | B | 1.69 | B |
| | | 61.4 | 8.1 | | B | 1.3 | B |
| B 15.9-5db | -- | 78.1 | 19.7 | 19.8 | P | 2.49 | 12.3 |
| | | 79.4 | 20.1 | | P | 1.1 | 8.7 |
| B 15.9-10db | -- | 84.1 | 10.6 | 10.7 | P | 3.07 | 4.9 |
| | | 86.3 | 10.8 | | P | 0.7 | 4.5 |
| B 15.9-15db | -- | 91.1 | 7.6 | 7.6 | P | 3.2 | 5.7 |
| | | 90.8 | 7.6 | | P | 2.4 | 4.2 |
| B 19-5db | -- | 98.3 | 17.3 | 17.3 | P | 3.3 | 12.8 |
| | | 98.4 | 17.4 | | P | 2.7 | 7.5 |
| B 19-10db | -- | 105.1 | 9.3 | 9.3 | P | 3.8 | 6.1 |
| | | 104.8 | 9.2 | | P | 2.1 | 3.4 |
| B 19-15db | -- | 110.6 | 6.5 | 6.5 | P | 4.4 | 4.4 |
| | | 109.7 | 6.4 | | P | 4.1 | 2.5 |
| ***Note:*** ţ = bond strength; P = pull-out; B = bar failure S$_{max.}$ = maximum slip | | | | | | | |

### 4.3.2 Conditioned Specimens

The behavior of bond strength of BFRP bar in high strength concrete after three months of immersion in seawater and the alkaline solution was also tested. Table 4. 5 and Table 4. 6 shows the pull-out results of high-strength concrete in the alkaline and seawater.

**Table 4. 5 Pull-out Test Results of High Strength Concrete in Seawater**

| Specimen | Environment | Time months | Peak Load KN | ţ$_{max}$ MPa | Avg. ţ$_{max}$ MPa | Failure Mode | $S_{max.}$ mm | Retention (%) | Residual ţ MPa |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | Sea | 3 | 48.1 | 19.0 | 18.90 | P | 1.53 | 84.1 | 6.4 |
| | | | 47.7 | 18.8 | | P | 0.9 | | 5.9 |
| B 12.7-10db | -- | -- | 50.2 | 9.91 | 10.0 | P | 1.21 | 83.4 | 4.4 |
| | | | 51.1 | 10.09 | | P | 0.8 | | 2.1 |
| B 12.7-15db | -- | -- | 58.2 | 7.66 | 77.65 | P | 1.39 | 94.6 | 4.8 |
| | | | 58.1 | 7.65 | | P | 1.35 | | 3.3 |
| B 15.9-5db | -- | -- | 64.1 | 16.15 | 15.91 | P | 2.1 | 80.2 | 6.3 |
| | | | 62.2 | 15.67 | | P | 1.4 | | 5.3 |
| B 15.9-10db | -- | -- | 68.9 | 8.68 | 8.76 | P | 1.9 | 81.6 | 4.8 |
| | | | 70.1 | 8.83 | | P | 1.5 | | 4.2 |
| B 15.9-15db | -- | -- | 72.4 | 6.08 | 6.11 | P | 3.5 | 80.0 | 4.0 |
| | | | 73.1 | 6.14 | | P | 2.7 | | 2.9 |
| B 19-5db | -- | -- | 78.3 | 13.82 | 13.74 | P | 2.5 | 79.2 | 10.4 |
| | | | 77.4 | 13.66 | | P | 2.1 | | 7.1 |
| B 19-10db | -- | -- | 84.9 | 7.50 | 7.54 | P | 2.9 | 81.5 | 6.4 |
| | | | 86.1 | 7.60 | | P | 2.7 | | 3.2 |
| B 19-15db | -- | -- | 88.7 | 5.22 | 5.23 | P | 3.9 | 80.7 | 4.5 |
| | | | 89.1 | 5.24 | | P | 4.1 | | 2.9 |

***Note:*** ţ = bond strength; P = pull-out; $S_{max.}$ = maximum slip;

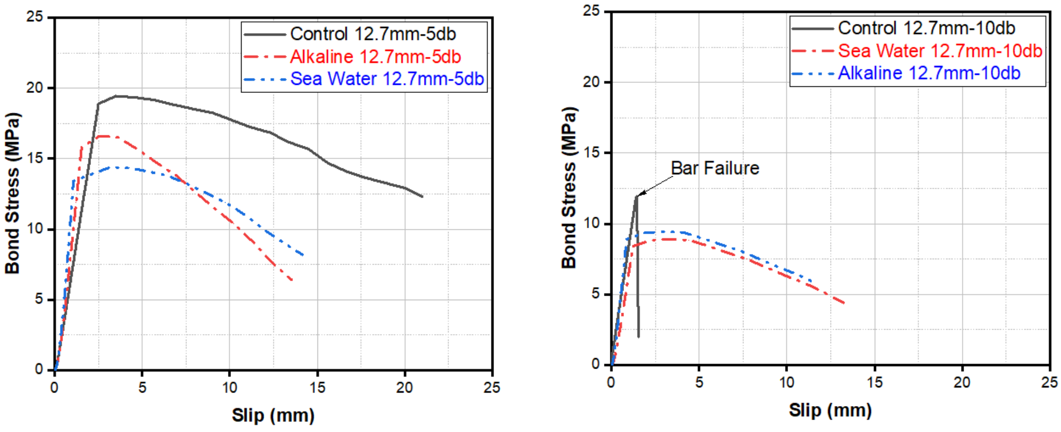
**Table 4. 6 Pull-out Test Results of High Strength Concrete in Alkaline Solution**

| Specimen | Environment | Time months | Peak Load KN | ţ$_{max}$ MPa | Avg. ţ$_{max}$ MPa | Failure Mode | $S_{max.}$ mm | Retention (%) | Residual ţ MPa |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | A | 3 | 49.1 | 19.39 | 19.65 | P | 1.1 | 87.4 | 8.2 |
| | | | 50.4 | 19.90 | | P | 0.9 | | 2.7 |
| B 12.7-10db | - | - | 53.2 | 10.50 | 10.6 | P | 1.45 | 88.3 | 5.7 |
| | | | 54.1 | 10.68 | | P | 0.85 | | 2.5 |
| B 12.7-15db | -- | -- | 57.1 | 7.52 | 7.47 | P | 1.5 | 92.4 | 5.4 |
| | | | 56.4 | 7.42 | | P | 1.2 | | 1.5 |
| B 15.9-5db | -- | -- | 68.2 | 17.18 | 17.33 | P | 1.8 | 87.4 | 9.4 |
| | | | 69.4 | 17.48 | | P | 1.5 | | 6.3 |
| B 15.9-10db | -- | -- | 72.4 | 9.12 | 9.15 | P | 2.3 | 85.3 | 5.2 |
| | | | 72.9 | 9.18 | | P | 0.9 | | 4.1 |
| B 15.9-15db | -- | -- | 76.2 | 6.40 | 6.45 | P | 2.7 | 84.5 | 4.1 |
| | | | 77.5 | 6.51 | | P | 2.9 | | 3.2 |
| B 19-5db | -- | -- | 80.4 | 14.19 | 14.29 | P | 2.9 | 82.4 | 10.5 |
| | | | 81.6 | 14.40 | | P | 2.1 | | 8.7 |
| B 19-10db | -- | -- | 88.4 | 7.80 | 7.75 | P | 3.1 | 83.7 | 7.0 |
| | | | 87.3 | 7.70 | | P | 2.9 | | 3.2 |
| B 19-15db | -- | -- | 90.1 | 5.30 | 5.36 | P | 2.9 | 82.8 | 4.5 |
| | | | 92.3 | 5.43 | | P | 3.3 | | 2.7 |

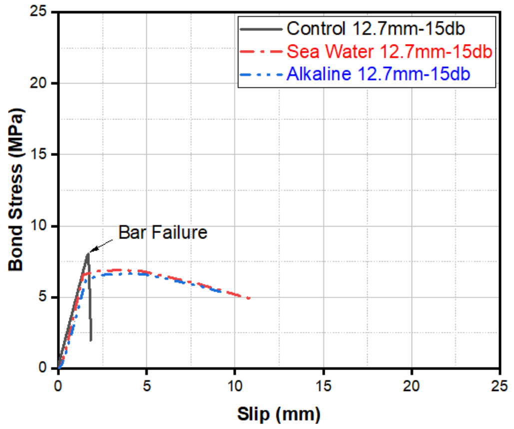
***Note:*** ţ = bond strength; P = pull-out; $S_{max.}$ = maximum slip; A = Alkaline Solution.

#### *4.3.2.1 Bond Stress-Slip relationship*

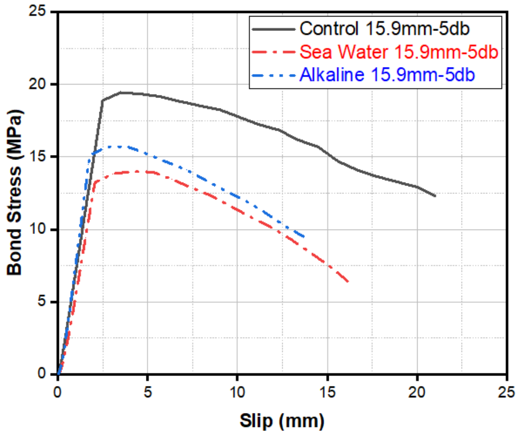
Figure 4. 3 shows the relationship between bond stress and slip in high-strength concrete. Split behavior was not observed with high-strength concrete. Bar pull-out failure was observed in high-strength concrete specimens because maximum bond stress value was achieved before the concrete split failure. Low slip value was observed as compared to normal strength concrete because of better bond performance of BFRP bar in high strength concrete. Bar Rupture failure was observed in a few of the specimens. Since the BFRP bar is anisotropic in nature, tensile load carrying capacity in the longitudinal direction is primarily because of the basalt fibers but in the transverse direction, it is due to the type of resin used in BRFP bars. Bar rupture failure was because of the failure of the resin. Bar Rupture failure could be nullified by using bars having high strength resin matrix.



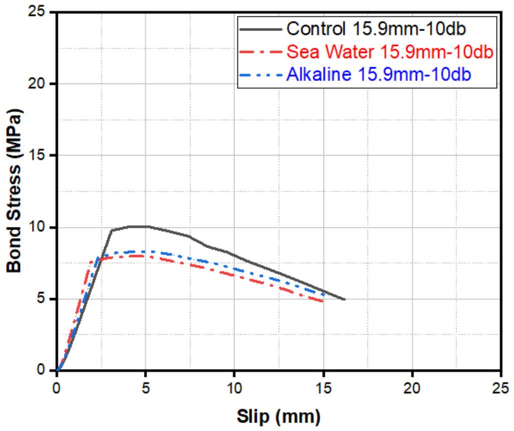
a) b)


Control 12.7mm-15db
Sea Water 12.7mm-15db
Alkaline 12.7mm-15db
Bar Failure
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

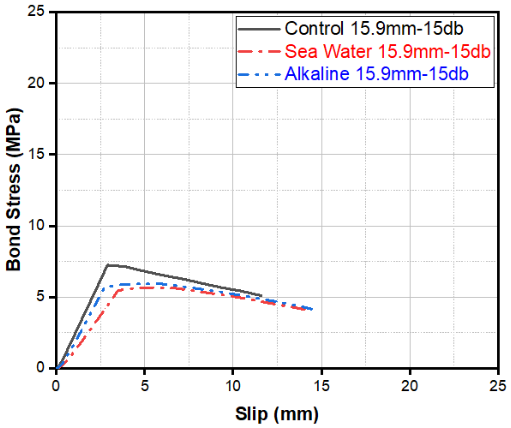
c)


Control 15.9mm-5db
Sea Water 15.9mm-5db
Alkaline 15.9mm-5db
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

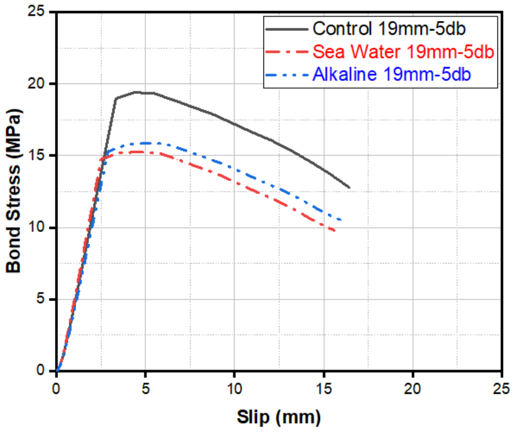
d)


Control 15.9mm-10db
Sea Water 15.9mm-10db
Alkaline 15.9mm-10db
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

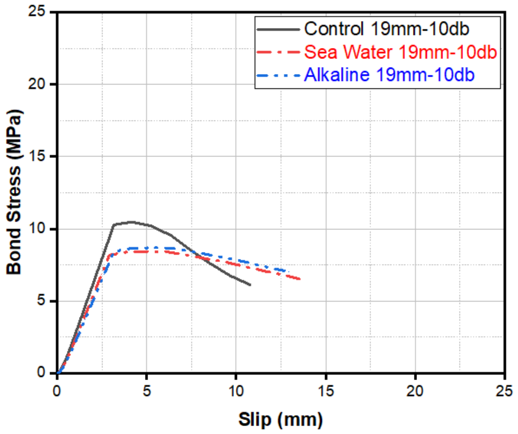
e)


Control 15.9mm-15db
Sea Water 15.9mm-15db
Alkaline 15.9mm-15db
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

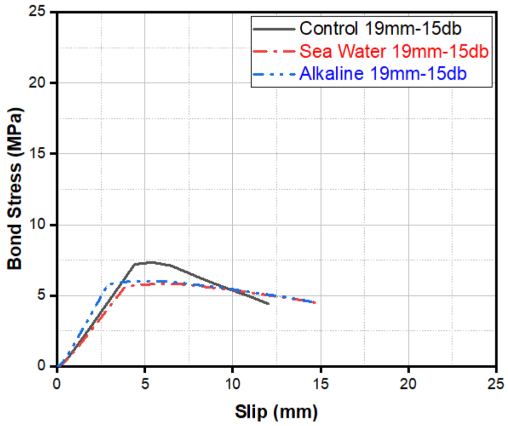
f)


Control 19mm-5db
Sea Water 19mm-5db
Alkaline 19mm-5db
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

g)


Control 19mm-10db
Sea Water 19mm-10db
Alkaline 19mm-10db
Bond Stress (MPa)
Slip (mm)
0
5
10
15
20
25

h)



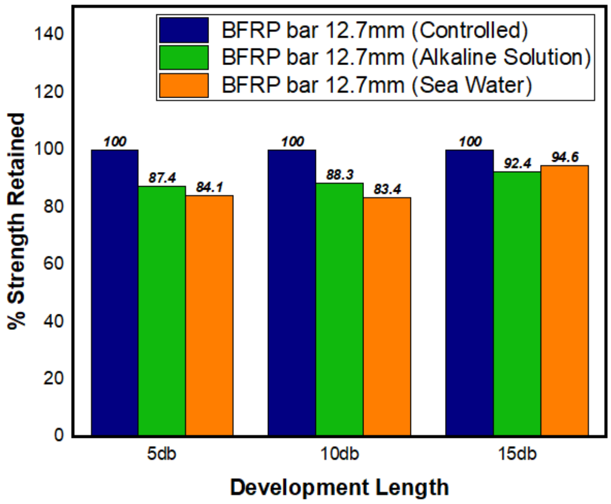
i)

**Figure 4. 3 Relationship between Stress-slip in High Strength Concrete**

#### *4.3.2.2 Comparison against different environments*

A maximum bond stress value of 22.5 MPa was observed in the controlled specimens. 19.65 MPa of bond stress value was observed with alkaline solution and 18.92 MPa bond stress value was observed when immersion in the seawater. The following graph shows the bond strength retention when high-strength concrete specimens were immersed in alkaline seawater for a period of three months.

a)



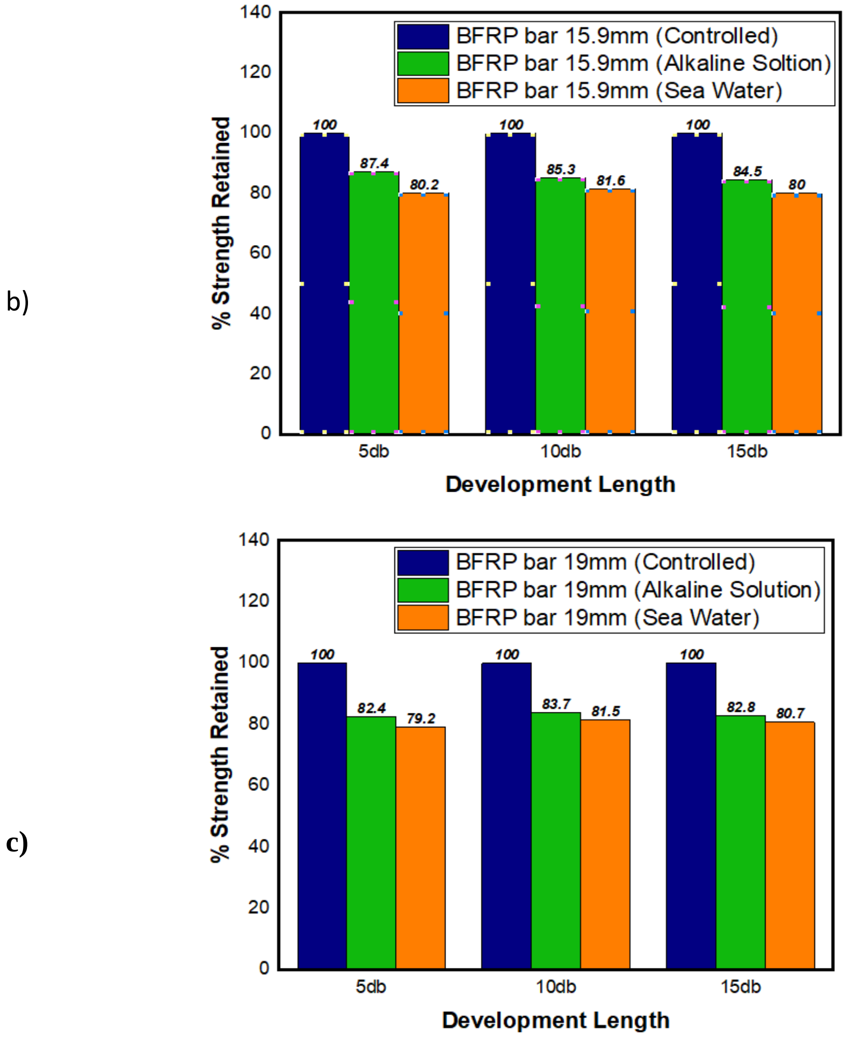


**Figure 4. 4 Relationship between % strength Retention and Development in High Strength Concrete a) 12.7mm b) 15.9 c) 19mm**

As can be seen from Figure 4. 4 that the bond stress performance of the Basalt FRP bar was better in the alkaline solution than the seawater. Bond strength retention was observed to be 82% to 92% when immersed in the alkaline solution and 80% to 94% bond strength retention in the case of seawater.

## 4.4 Geopolymer Concrete

Bond stress performance of BFPR bars in the case of geopolymer concrete was also studied against different parameters. Geopolymer concrete was also studied in both conditioned and unconditioned environments.

### 4.4.1 Unconditioned Specimens

Geopolymer concrete specimens were cast and cured in cling wraps for 28 days, representing the ambient curing condition. Just like other types of concrete, 18 specimens were tested to study the behavior of bond stress for different bar diameters and bond length in an unconditioned environment. Table 4. 7 shows the test results against the direct pull-out test.

**Table 4. 7 Pull-out Results of Geopolymer Concrete in Controlled Environment**

### 4.4.2

| Specimen | Time months | Peak Load KN | $\tau_{max}$ MPa | Avg. $\tau_{max}$ MPa | Failure Mode | Slip mm | Residual $\tau$ MPa |
|---|---|---|---|---|---|---|---|
| B 12.7-5db | 1 | 38.5 | 15.20 | 15.32 | P | 1.06 | 5.5 |
| | | 39.1 | 15.44 | | P | 0.95 | 4.2 |
| B 12.7-10db | -- | 42.1 | 8.31 | 8.48 | P | 1.45 | 3.2 |
| | | 43.8 | 8.65 | | P | 0.75 | 2.2 |
| B 12.7-15db | -- | 48.1 | 6.33 | 6.32 | S | - | - |
| | | 47.9 | 6.31 | | S | - | - |
| B 15.9-5db | -- | 55.4 | 13.96 | 14.23 | S | - | - |
| | | 57.6 | 14.51 | | S | - | - |
| B 15.9-10db | -- | 60.1 | 7.57 | 7.62 | S | - | - |
| | | 60.8 | 7.66 | | S | - | - |
| B 15.9-15db | -- | 64.2 | 5.39 | 5.38 | S | - | - |
| | | 63.9 | 5.37 | | S | - | - |
| B 19-5db | -- | 78.1 | 13.78 | 13.98 | S | - | - |
| | | 80.4 | 14.19 | | S | - | - |
| B 19-10db | -- | 81.1 | 7.15 | 7.12 | S | - | - |
| | | 80.4 | 7.09 | | S | - | - |
| B 19-15db | -- | 84.1 | 4.95 | 4.92 | S | - | - |
| | | 83.2 | 4.89 | | S | - | - |

***Note:*** $\tau$ = bond strength; P = pull-out; B = bar failure $S_{max.}$ = maximum slip; S = Split failure of concrete

### 4.4.3 Conditioned environments

After 28 days of curing in ambient conditions, 18 geopolymer concrete specimens were immersed in the seawater and alkaline solution. Table 4. 8 and Table 4. 9 show the results of the pull-out test of geopolymer concrete reinforced with the BFRP bars.

**Table 4. 8 Pull-out test Results of Geopolymer concrete in Seawater**

| **Specimen** | **Environment** | **Time months** | **Peak Load KN** | **$\tau_{max}$ MPa** | **Avg. $\tau_{max}$ MPa** | **Failure Mode** | **$S_{max.}$ mm** | **Retention (%)** | **Residual $\tau$ MPa** |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | Sea | 3 | 31.1 | 12.28 | 12.54 | P | 1.2 | 81.83 | 2.9 |
| | | | 32.4 | 12.79 | | P | 0.75 | | 3.5 |
| B 12.7-10db | -- | -- | 35.2 | 6.95 | 6.94 | P | 1.1 | 81.84 | 3.2 |
| | | | 35.1 | 6.93 | | P | 0.9 | | 2.1 |
| B 12.7-15db | -- | -- | 38.7 | 5.09 | 5.13 | P | 1.1 | 81.15 | 2.6 |
| | | | 39.2 | 5.16 | | P | 1.3 | | 2.1 |
| B 15.9-5db | -- | -- | 45.6 | 11.49 | 11.56 | P | 1.5 | 81.24 | 6.8 |
| | | | 46.2 | 11.64 | | P | 1.4 | | 5.3 |
| B 15.9-10db | -- | -- | 50.1 | 6.31 | 6.26 | S | - | 82.22 | - |
| | | | 49.3 | 6.21 | | S | - | | - |
| B 15.9-15db | -- | -- | 53.4 | 4.48 | 4.56 | S | - | 84.79 | - |
| | | | 55.22 | 4.64 | | S | - | | - |
| B 19-5db | -- | -- | 63.2 | 11.15 | 11.21 | S | - | 80.19 | - |
| | | | 63.9 | 11.27 | | S | - | | - |
| B 19-10db | -- | -- | 66.2 | 5.84 | 5.88 | S | - | 82.54 | - |
| | | | 67.1 | 5.92 | | S | - | | - |
| B 19-15db | -- | -- | 69.1 | 4.06 | 4.08 | S | - | 83.02 | - |
| | | | 69.8 | 4.11 | | S | - | | - |
| ***Note:*** $\tau$ = bond strength; P = pull-out; $S_{max.}$ = maximum slip; S = Split failure of concrete | | | | | | | | | |

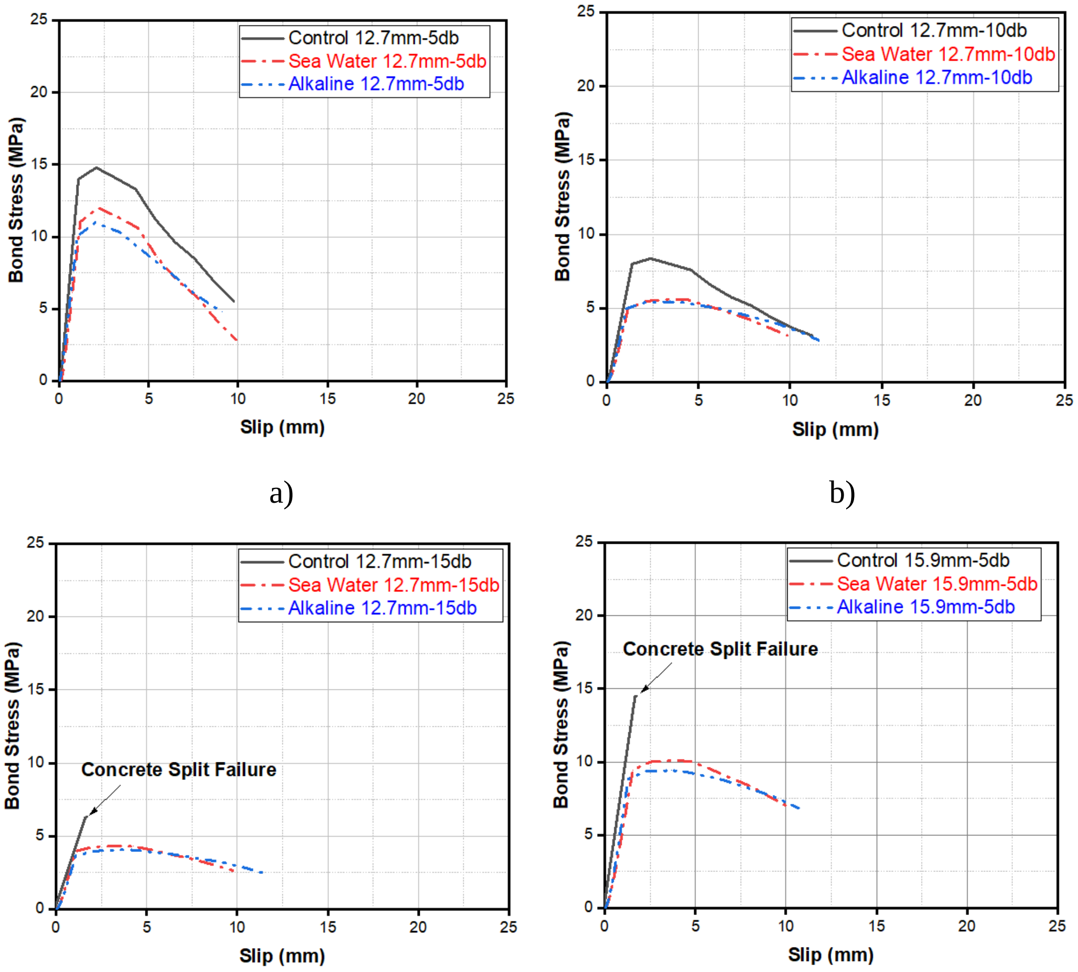
**Table 4. 9 Pull-out Test Results of Geopolymer Concrete in Alkaline Solution**

| **Specimen** | **Environment** | **Time months** | **Peak Load KN** | **ţ$_{max}$ MPa** | **Avg. ţ$_{max}$ MPa** | **Failure Mode** | **S$_{max.}$ mm** | **Retention (%)** | **Residual ţ MPa** |
|---|---|---|---|---|---|---|---|---|---|
| B 12.7-5db | A | 3 | 29.7 | 11.7 | 11.6 | P | 1.0 | 75.8 | 4.8 |
| | | | 29.1 | 11.5 | | P | 0.75 | | 3.1 |
| B 12.7-10db | -- | -- | 33.4 | 6.6 | 6.5 | P | 1.1 | 76.3 | 2.8 |
| | | | 32.1 | 6.3 | | P | 0.8 | | 2.4 |
| B 12.7-15db | -- | -- | 37.7 | 5.0 | 4.9 | P | 1.1 | 77.1 | 2.4 |
| | | | 36.3 | 4.8 | | P | 1.2 | | 1.9 |
| B 15.9-5db | -- | -- | 43.2 | 10.9 | 10.8 | P | 1.5 | 75.8 | 6.8 |
| | | | 42.4 | 10.7 | | P | 1.1 | | 6.3 |
| B 15.9-10db | -- | -- | 48.1 | 6.1 | 6.0 | S | - | 78.8 | - |
| | | | 47.2 | 5.9 | | S | - | | - |
| B 15.9-15db | -- | -- | 50.2 | 4.2 | 4.2 | S | - | 77.7 | - |
| | | | 49.3 | 4.1 | | S | - | | - |
| B 19-5db | -- | -- | 61.1 | 10.8 | 10.8 | S | - | 76.9 | - |
| | | | 60.8 | 10.7 | | S | - | | - |
| B 19-10db | -- | -- | 63.1 | 5.6 | 5.6 | S | - | 78.2 | - |
| | | | 63.2 | 5.6 | | S | - | | - |
| B 19-15db | -- | -- | 66.1 | 3.9 | 3.9 | S | - | 78.5 | - |
| | | | 65.2 | 3.8 | | S | - | | - |

***Note:*** ţ = bond strength; P = pull-out; S$_{max.}$ = maximum slip; A = Alkaline Solution; S = Split failure of concrete

### *4.4.3.1 Bond stress-slip relationship*

Most of the geopolymer concrete specimens show the concrete split failure-like behavior observed in normal strength concrete. As the strength of geopolymer concrete and normal strength concrete was the same, a similar kind of failure pattern was observed. Split failure was observed in geopolymer concrete, which shows that maximum concrete split value was achieved before reaching maximum bond stress. Figure 4. 5 shows the stress-slip relationship of BFRP reinforced in geopolymer concrete.



a)

b)

c)

d)

**Figure 4. 5 Relationship between Bond stress-slip in Geopolymer Concrete**

Few geopolymer specimens show pull-out behavior in both conditioned and unconditioned environments.

### *4.4.3.2 Comparison against different environments*

A maximum bond stress value of 15.32 MPa was observed in the case of the controlled specimens. 11.61 MPa of bond stress value was observed in the case of alkaline solution and 12.54 MPa bond stress value was observed when immersion in the seawater.

Figure 4. 6 shows the bond strength retention when high-strength concrete specimens were immersed in alkaline and seawater for a period of three months.

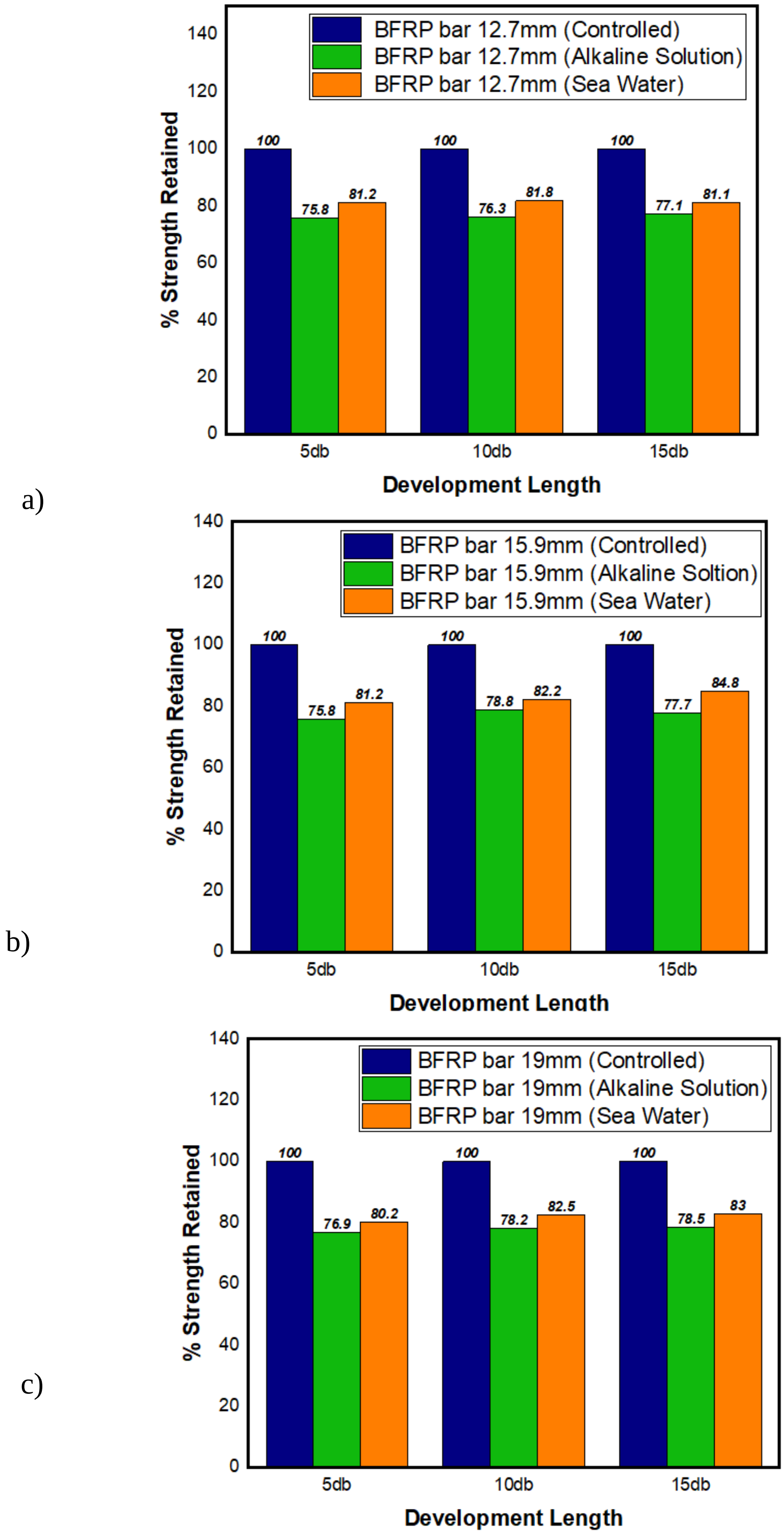
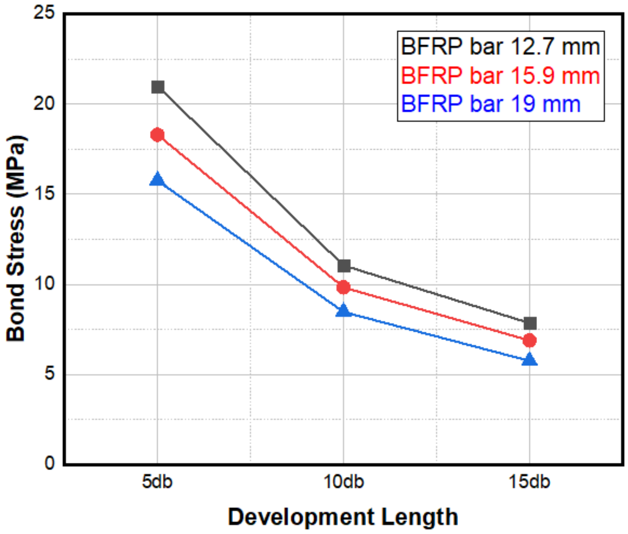


**Figure 4. 6 Relationship between % stress retention and Development Length in Geopolymer Concrete a) 12.7 mm b) 15.9 mm c) 19 mm**

As can be seen from the graphs, the bond stress performance of the basalt FRP bar was better in seawater than the alkaline solution. 75% to 79% of bond strength retention was observed when immersed in the alkaline solution and 80% to 85% bond strength retention was observed with seawater.

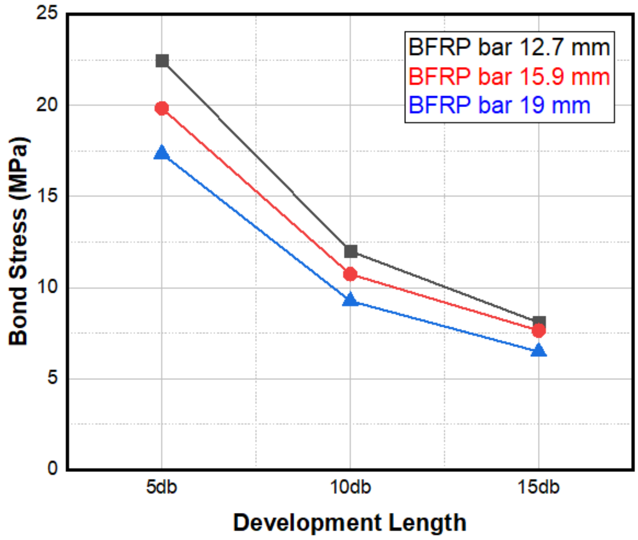
## 4.5 Comparison between bond stress varying bar diameter and embedment length

As studied from the literature (Achillides 1998; Achillides and Pilakoutas 2004b; Refai et al. 2015) with the increase in bar diameter and the embedment length, bond stress degrades. A similar type of behavior was confirmed in each concrete type. Figure 4. 7 show the relationship between bond stress and development length in each type of concrete.



a)

b)



c)

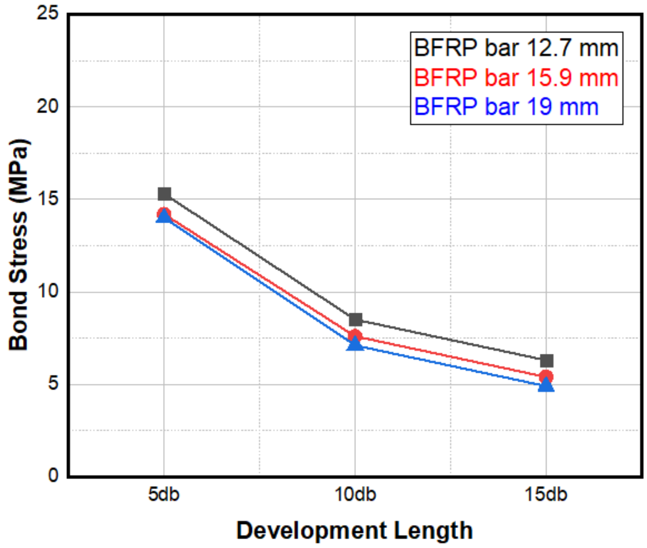
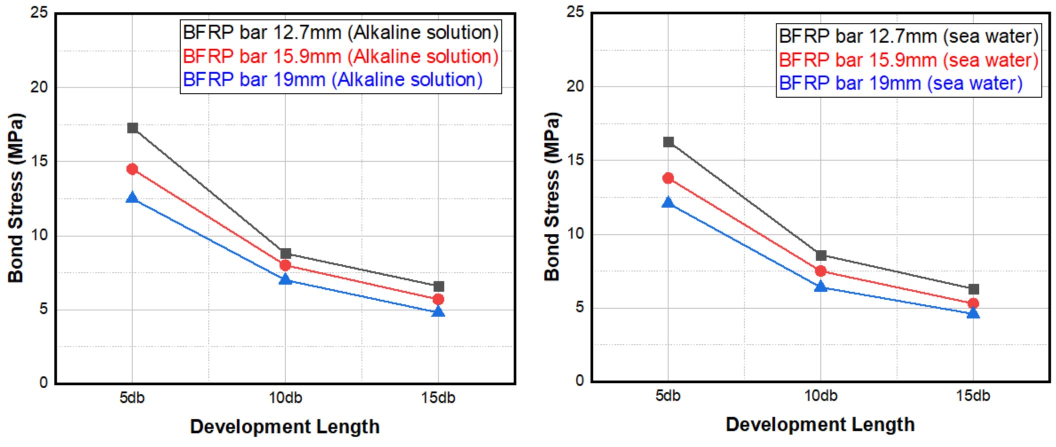


**Figure 4. 7 Relationship between Bond Stress and Development Length a) Normal Strength Concrete b) High Strength Concrete c) Geopolymer Concrete**

A similar kind of behavior was also observed when concrete specimens were submerged in alkaline solution and seawater, as shown below Figure 4. 8, Figure 4. 9, and Figure 4. 11. With the increase in the bar diameter and embedment length, bond stress reduces primarily due to two factors.

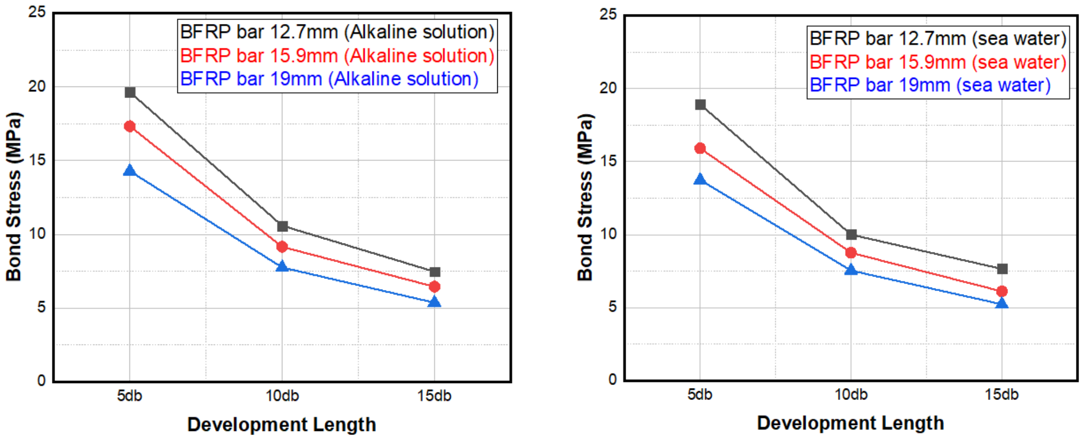
1. As concrete is a non-homogeneous material, with an increase in the embedment length, nonlinear stress distribution increase between the inner and outer fibers of the bar.

2. Because of Poisson's effect, bar diameter reduces with indeed degrades the friction between concrete-BFRP bar interface. Reduction in the bar diameter is also shown in Figure 4. 11.



a) b)

**Figure 4. 8 Relationship between Bond Stress and Development in Normal Strength Concrete a) Alkaline Solution b) Seawater**



a) b)

**Figure 4. 9 Relationship between Bond stress and Development Length in High Strength Concrete a) Alkaline Solution b) Seawater**

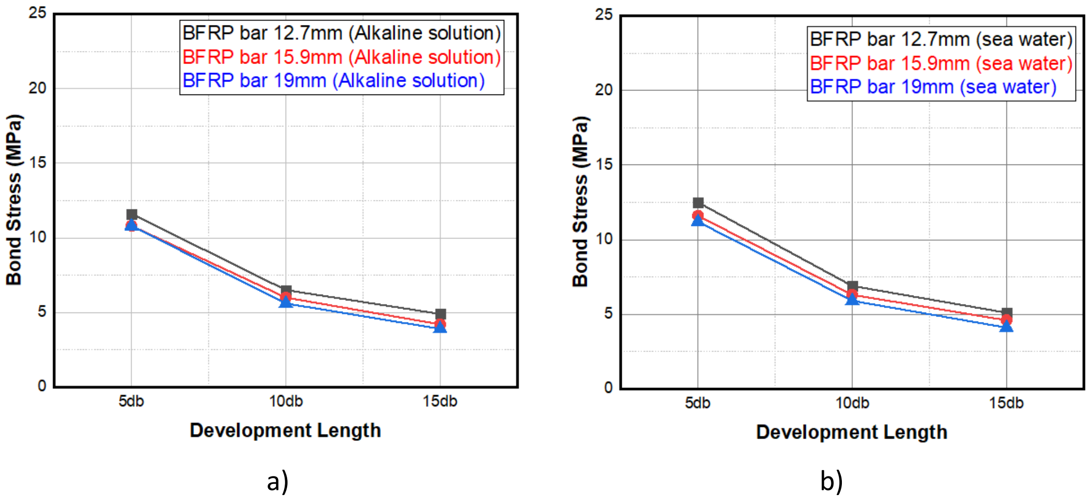


**Figure 4. 10 Relationship between Bond stress and Development Length in Geopolymer Concrete a) Alkaline Solution b) Seawater**

**a)** **b)**

**Figure 4. 11 Reduction in the Bar Diameter a) Before Pull-out test b) After Pull-out Test**

## 4.6 Comparison between bond stress and aggressive environments

When using normal strength and high strength concrete, the bond strength performance was better in alkaline solution than in sea water. But with geopolymer concrete, bond stress was better in seawater as compared with alkaline solution. When the concrete specimen was immersed in the seawater bond strength reduction was mainly because of the deterioration of the resin matrix (Lu and Xian 2016). When the resin matrix which holds together BFRP fiber in the bar degrades, chloride ions ($Cl^-$) breaches into basalt fibers and react with ferrous ions ($Fe^{+2}$) which are already present in the basalt fibers

(Guo et al. 2018; Wang et al. 2018). The reaction yields $Fe_2O_3.nH_2O$ which is an expansive product that leads to degrades the interfacial surface bond between the BFRP bar and concrete. Figure 4. 12 shows the comparison of BFRP bars before and after immersion in seawater.

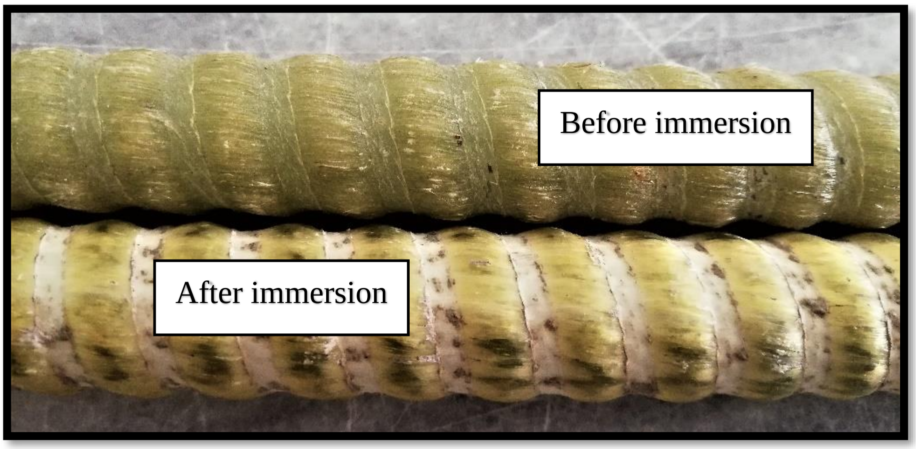


**Figure 4. 12 BFRP bar before and After Immersion to the Seawater**

With the visual inspection, deterioration of the resin matrix was observed. Bond stress degradation in the case of the alkaline solution is primarily because of the failure of the Si-O-Si bond. This bond is degraded because of the formation of an ester bond in the resin matrix formed by the hydroxyl ions (Lu and Xian 2016).

## 4.7 Comparison between bond stress and concrete strength

No appreciable difference of bond stress was observed, as the concrete strength was increased from 25 MPa to 60 MPa. As mentioned in the literature (Achillides and Pilakoutas 2004a), after increasing the concrete strength from 35 MPa to 40 MPa, concrete strength doesn’t affect the bond stress significantly. Concrete split failure governs in the concrete strength less than 30 MPa whereas a further increase in the concrete strength up to 40 MPa, failure shifts from concrete to the interfacial bond surface between the concrete and the BFRP bar. With the high strength concrete, concrete bond performance was better than that of normal strength concrete and geopolymer concrete, because of the lesser penetration of the aggressive media in the dense matrix of the concrete. Figure 4. 16 shows the different types of failure patterns observed in this research.

## 4.8 Future bond strength prediction model

With of passage of time, the bond between the concrete and reinforcing bar tends to degrade when concrete is subjected to different kinds of aggressive environments. So, the future bond strength prediction is important to fully understand the bond behavior of reinforcing bars in concrete.

### 4.8.1 Fib Bulletin model

Fib bulletin model is used to predict the future bond stress of FRP bars in concrete. Few researchers (Lu et al. 2021) used this model to predict the bond performance in their research. This model uses the bond degradation factor to get future results. Bond strength is calculated by the equation.

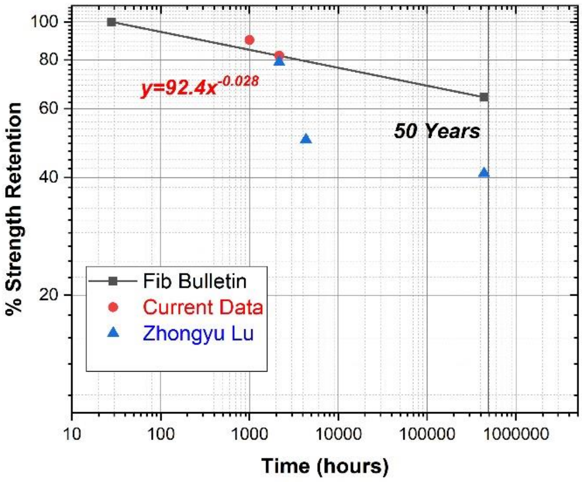
$$\eta_{evn,b} = {}^{1}\Big/_{\left[\frac{(100 - R_{10})}{100}\right]^{n}}$$

Where $n_T$, $n_{mo}$, and $n_{SL}$ are the parameters used for the temperature, moisture condition, and serviceability life, respectively. Values of $n_T$, $n_{mo}$, and $n_{SL}$ are taken from the literature according to my research parameters. Table 4. 10 shows the results of the fib bulletin method.

**Table 4. 10 Fib Bulletin Model Results for the Future Prediction of Bond Stress**

| | **Specimen** | **immersion media** | **Temperature** | **R10 %** | **$n_T$** | **n** | **nenv, b** | **1/nenv, b** |
|---|---|---|---|---|---|---|---|---|
| HSC | BFRP | sea water | 26 | 11 | 1 | 4.7 | 1.7293 | 0.5783 |
| | BFRP | Alkaline solution | 26 | 9 | 1 | 4.7 | 1.55778 | 0.64194 |
| NSC | BFRP | sea water | 26 | 14 | 1 | 4.7 | 2.03169 | 0.4922 |
| | BFRP | Alkaline solution | 26 | 11 | 1 | 4.7 | 1.72929 | 0.57827 |
| GPC | BFRP | sea water | 26 | 12 | 1 | 4.7 | 1.82361 | 0.54836 |
| | BFRP | Alkaline solution | 26 | 16 | 1 | 4.7 | 2.26928 | 0.44067 |

Figure 4. 13 shows the results of the future bond performance of BFRP bars in high strength in a conditioned environment.



a)

b)

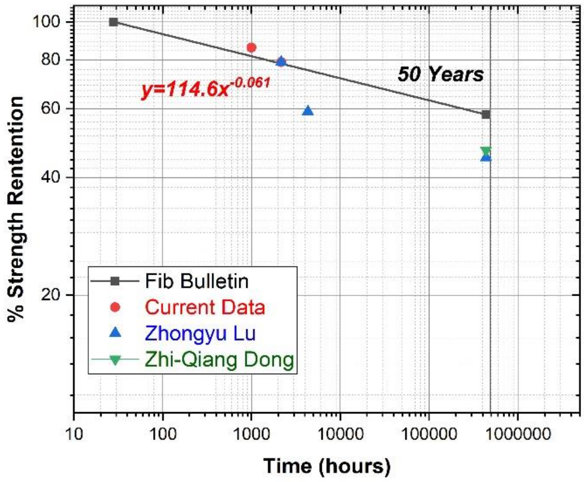
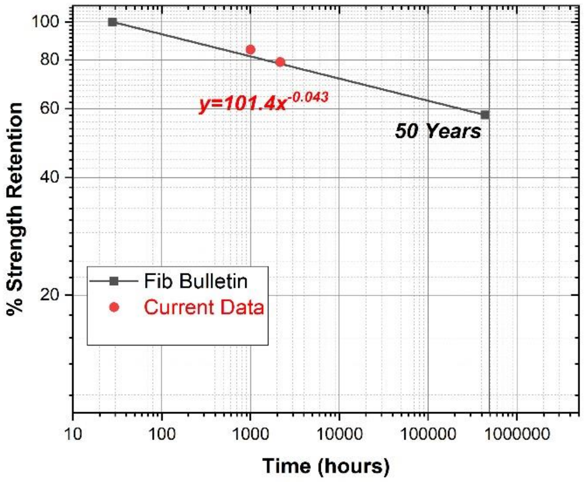


**Figure 4. 13 High Strength Concrete Future Bond Stress Prediction a) Alkaline Solution b) Seawater**

High strength concrete when reinforced with BFRP bar, 64.2% of bond strength retention was observed in case of alkaline solution and 57.8% of bond strength retention was observed in seawater.

Figure 4. 14 shows the results of normal strength concrete when reinforced with BFRP bars.

a)



b)

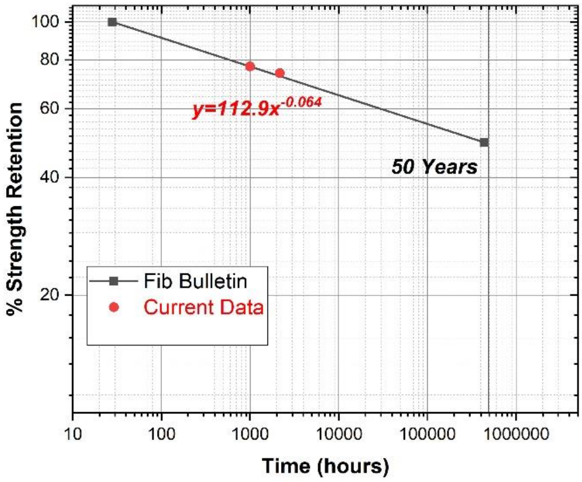
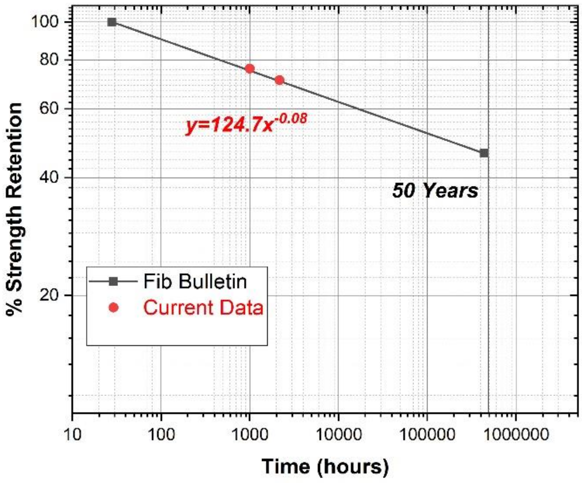
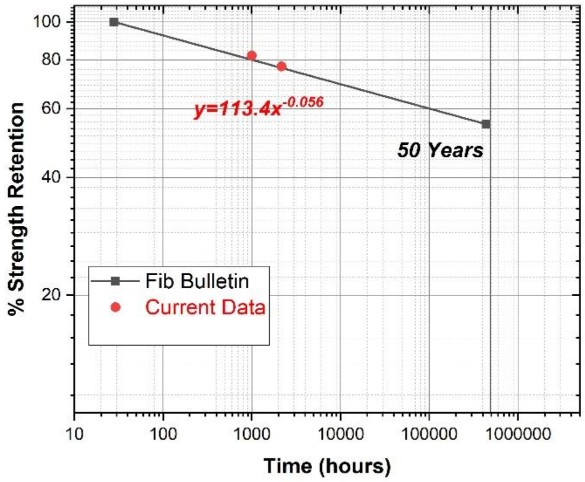


**Figure 4. 14 Normal Strength Concrete Future Bond Strength Prediction a) Alkaline Solution b) Seawater**

57.8% and 49.2% of bond strength retention were observed when normal strength concrete was immersed in alkaline solution and seawater, respectively. Figure 4. 15 shows the result of geopolymer concrete when reinforced with BFRP bars.

a)

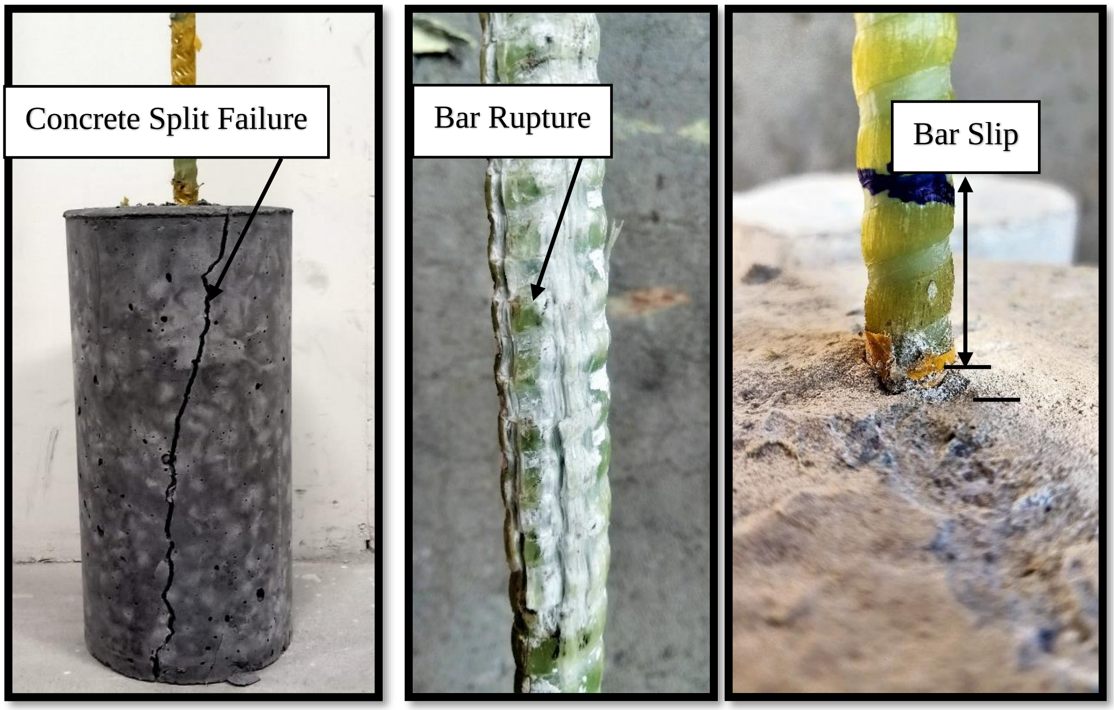




b)

**Figure 4. 15 Geopolymer Concrete Future Bond Stress Prediction a) Alkaline Solution b) Seawater**

44% and 54.8% bond strength retention were predicted with alkaline solution and seawater, respectively.



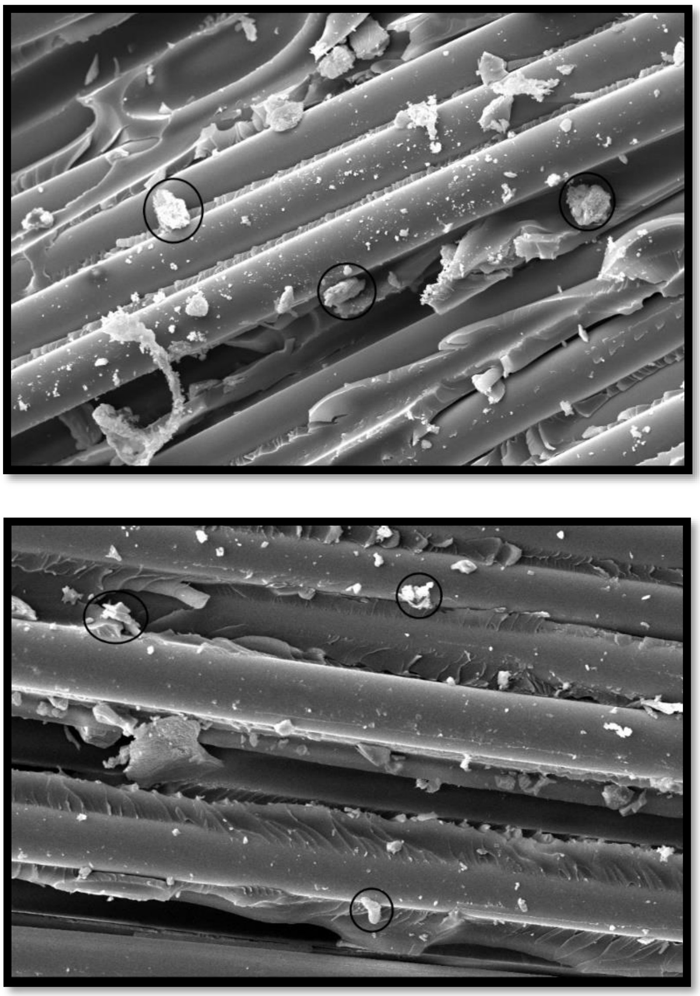
a) b) c)

**Figure 4. 16 Failure Pattern a) Concrete Split Failure b) Bar Rupture Failure**

**c) Bar Pull-out**

## 4.9 SEM Analysis

For the SEM analysis, BFRP was extracted from the bonded region. Error! Reference source not found. shows the SEM results of BFRP bar in both alkaline and seawater. Degradation of resin matrix can be seen from the figures. EDX was done to find out the chemical compositions of the elements present there. EDX results showed the chloride and calcium ions intrusion on the fibers and resin matrix in seawater and alkaline solution, respectively. Expansions of the basalt fibers can be seen in both scenarios, which leads to the bond failure between the concrete and BFRP bar.



a)

b)

**Figure 4. 17 SEM analysis a) Alkaline Solution b) Seawater**

# CONCLUSIONS AND RECOMMENDATIONS

In this research total number of 164 concrete cylinders of size 150x300 mm were prepared for the direct pull-out test. Three different bar diameters of Basalt FRP bars (12.7, 15.9, and 19 mm) were used, with three different embedment lengths (5db, 10db, and 15db) were used. Three different types of concretes were used in this research.

- Normal strength concrete.
- High-strength concrete.
- Geopolymer concrete.

54 specimens were cured in the unconditioned environment for 28 days and then tested with the direct pull-out test. 54 specimens after 28 days of curing were immersed into the alkaline solution of pH 13~14 prepared in the laboratory for three months and then taken out for the pull-out test. 54 specimens after 28 days of curing were immersed into the seawater for three months and then tested for the direct pull-out test in the UTM machine. Maximum tensile load, as well as the slip values, were noted. In the end, the Fib bulletin model was used to predict the bond performance of the Basalt FRP bar for 50 years. After, a detailed study of the results following conclusions are drawn from the results.

## 5.1 Conclusions

- High-strength concrete showed better bond performance than the normal strength concrete and geopolymer concrete.
- Maximum bond strength was observed with the 12.7 mm diameter of bar and 5db embedment length in all the scenarios.

- Bond performance of the Basalt FRP was better were immersed in the alkaline solution for three months in both normal and high strength concrete.
- With geopolymer concrete bond performance of the Basalt, FRP bar was better in seawater than in the alkaline solution.
- Alkali activators (Sodium Hydroxide and Sodium Silicate) affected the bond performance of Basalt FRP bar in the geopolymer concrete more than the normal strength and high strength concrete, which results in the lower bond stress value in alkaline solution than the seawater.
- Because of the dense matrix and low porosity of the high-strength concrete, the penetration of the aggressive media was lesser than the normal strength, and geopolymer concrete results in the better bond performance of the Basalt FRP bar.
- There was no significant increase in the bond stress value in the high strength concrete than the normal strength concrete which shows the sign that by preparing the concrete of strength up to 40 MPa bond stress could also be studied since the failure will shift from the concrete surface to the interfacial concrete-bar surface.
- In normal strength as well as in geopolymer concrete the concrete, split failure was governing, which shows that before reaching the maximum bond stress value, concrete split failure occurred.
- In high strength, concrete bar pull-out failure was governing in most of the specimens, as few of the specimens showed the bar rupture failure, which was primarily because of the failure of the resin matrix.
- The value of residual bond stress was higher with high-strength concrete than the normal strength and geopolymer concrete.

- Fib bulletin model was used to predict the 50 years bond performance of the Basalt FRP bar in the concrete.
    - With high strength concrete bond strength, retention came to be 64.2% and 51.9% in the alkaline and seawater, respectively.
    - With normal strength, concrete bond strength retention came to be 57.8% and 49.2% in the alkaline and seawater, respectively.
    - With Geopolymer concrete bond strength retention came to be 44% and 54.8% in the alkaline and seawater, respectively.

## 5.2 Recommendations

Further study is required in the following areas:

- Within the scope of this research, changing the resin matrix bond performance needed to be studied.
- Bond performance of Basalt FRP bar needed to be studied with different bar surface treatments.
- The bond performance of Basalt FRP in geopolymer concrete needed to be studied in detail as the demand for geopolymer concrete is increasing.
- A new future bond strength prediction model is required which should incorporate the parameters such as concrete strength bar diameter and development length as they play a key role in the bond strength.

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