

**INVESTIGATING STUDY OF THE EFFECT OF BASALT
FIBER CONTENT ON SEAWATER SEA SAND
CONCRETE AND SEAWATER SEA SAND MORTAR**

BY

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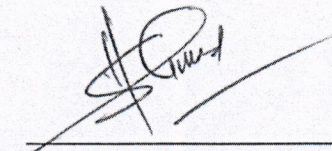
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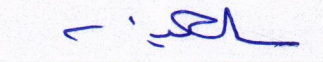
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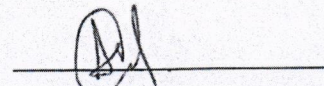


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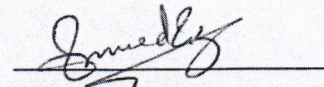


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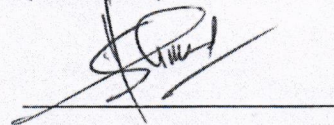
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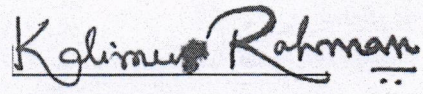
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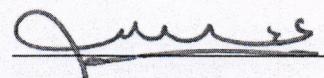
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After all praise to Allah Almighty SWT who gave me everything and blessed me with more than I ever deserved. This thesis is dedicated to my father Prof. Ammar Aldaddou, to my mother Rehab Younso, my wife Rokaya Alwan, my advisor Dr. Asad Hanif, to my great teachers, and to all my friends who supported me along this long journey. |

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LIST OF ABBREVIATION

ANOVA	:	Analysis of Variance.
ASTM	:	American Society of Testing and Materials.
BF	:	Basalt Fiber.
BFRC	:	Basalt Fiber Reinforced Concrete.
BFRN	:	Basalt Fiber Reinforced Mortar.
BFR-SSSM	:	Basalt Fiber Reinforced Seawater Sea Sand Concrete.
BFR-SSSM	:	Basalt Fiber Reinforced Seawater Sea Sand Mortar.
EDS	:	Energy Dispersive X-Ray Spectroscopy.
GFRP	:	Glass Fiber Reinforced Polymers.
ISE	:	Ion Selective Electrode.
LSD	:	Least Significant Difference.
OC	:	Ordinary Concrete.
OPC	:	Ordinary Portland Cement.
ICP-OES	:	Inductively Coupled Plasma – Optical Emission Spectrometry.
RCPT	:	Rapid Chloride Penetration Test.

SEM	:	Scanning Electron Microscopy.
SSSC	:	Seawater Sand Concrete.
SSSM	:	Seawater Sea Sand Mortar.
XRD	:	X-Ray Diffraction.

ABSTRACT

Full Name : [Amin Ammar Aldaddou]
Thesis Title : [Investigating Study of The Effect of Basalt Fiber Content on Seawater
Sea Sand Concrete and Seawater Sea Sand Mortar]
Major Field : [Civil Engineering]
Date of Degree : [December 2024]

The industry of concrete structures throughout the years has been accountable for consuming a significant quantity of raw materials including drinkable water, limestone, sand, and steel, despite the materials' high environmental and economic implications. As well as polluting the environment and leaving a high carbon footprint throughout the manufacturing process. Therefore, intensive research has been conducted on finding alternative renewable materials that are less costly, less harmful to the environment with a smaller carbon footprint, and more approachable. In this research, green cementitious mixes are introduced where basalt fibers (BF) are used to reinforce seawater sea sand concrete (SSSC) and seawater sea sand mortar (SSSM). Seawater, sea sand, and basalt fibers are used as alternatives to fresh water, normal sand, and steel fiber respectively, where the latter materials are mostly more expensive, more valuable, and are heavily demanded in many industries alongside the construction industry. This research is conducted to study the mechanical behavior, microstructure, and durability of SSSC and SSSM reinforced with different basalt fiber content. Workability, compressive strength, flexural strength, split tensile strength, toughness, elastic modulus, durability, and microstructure are studied in this research where tests are conducted on different BF contents at different ages for both SSSC and SSSM. Results show that basalt fiber content highly enhances the flexural strength of SSSM and SSSC along with the split tensile

strength of SSSC, increasing their ductility without significantly impacting their compressive strength. However, it is found that basalt fibers highly affect the workability of both SSSC and SSSM. It is also found that basalt fibers increase the ability of SSSM to resist shrinkage significantly and has no significant impact on either the initial or final setting time of SSSM. Slight increasing in elasticity of SSSC with the addition of basalt fibers is observed and it is also found that basalt fibers increase the toughness of SSSC and SSSM significantly. In addition, it is observed that basalt fibers mildly enhance the water absorption of SSSC when used in the mix. The applications of such materials are very wide, especially for oil companies when constructing pipelines near remote shores and in marine environments, which will directly affect the cost of raw materials transportation and solve other logistic problems.

ملخص الرسالة

الاسم الكامل: أمين عمار الددو

عنوان الرسالة: دراسة لتأثير الألياف البازلتية على الخرسانة المصنوعة بالماء البحري والرمل البحري.

التخصص: الهندسة المدنية

تاريخ الدرجة العلمية: مايو 2024.

خلال السنوات الأخيرة أصبحت عملية تصنيع وإنتاج الخرسانة مسؤولة عن جزء كبير من استهلاك المواد الخام مثل الحجر الجيري وماء الشرب والحديد ، إضافة إلى أثرها الكبير في تلويث البيئة. لذلك اتجه كثير من الباحثين إلى إيجاد حلول لهذه المشاكل بالبحث عن مواد متجددة بديلة، تكون أقل تكلفة وأقل ضررا على البيئة ببصمة كربونية أصغر. في هذا البحث تم العمل على دراسة خلطات إسمنتية جديدة لم يتم العمل عليها من قبل، حيث تمت الدراسة على خلطات إسمنتية تتكون من ماء البحر ورمل البحر مسلحة بألياف البازلت الطبيعية. في هذه الخلطات تم استبدال ماء الشرب بماء البحر، واستبدال الرمل العادي برمل البحر. كما تم استبدال ألياف الحديد بألياف البازلت الطبيعية. هذه المواد البديلة أكثر وفرة من المواد المستخدمة سابقا، كما أن تصنيعها وإنتاجها أقل تكلفة وأقل ضررا على البيئة بشكل كبير، واستخدامها يقلل من الطلب الكبير والمتزايد على المواد الخام غير المتجددة. تم عمل هذا البحث لدراسة مختلف الخواص الميكانيكية، والتركيب المجهري، والصمود الزمني للخرسانة الاسمنتية المصنوعة بماء البحر ورمل البحر والمونة الاسمنتية المصنوعة بماء البحر ورمل البحر المسلحة بألياف البازلت الطبيعية. تم عمل اختبارات لقوى الضغط وقوى الشد وقابلية التشغيل والصمودية، بالإضافة إلى دراسة التركيب المجهري للخلطات الخرسانية والمونة المصنوعة بماء البحر ورمل البحر، حيث تم تجهيز ثلاث عينات لثلاثة أعمار مختلفة لكل خلطة. الخلطات تحتوي على كميات مختلفة من ألياف البازلت تبدأ من 0% إلى 2% للمونة و 0% إلى 1.5% للخرسانة. أظهرت النتائج أن محتوى ألياف البازلت يحسن بشكل كبير تحمل الخرسانة وكذلك المونة المصنوعين من ماء البحر ورمل البحر لقوى الشد

وتأثيره كذلك على اللدونة الخاصة بهما. كذلك أظهرت أن تأثير محتوى ألياف البازلت ليس له تأثير كبير على قوى الضغط فيهما. لكن على الجهة الأخرى، لوحظ أن محتوى ألياف البازلت يؤثر بشكل سلبي على إمكانية تشغيل الخرسانة وقت الخلط. تطبيق هذه الخلطات في الحياة العملية واسع وممكن جدا، خصوصا في قطاع النفط والبنية التحتية للشركات التي تعمل في أماكن نائية قرب السواحل، حيث استخدام هذه المواد في المنشآت تلك يؤثر بشكل مباشر وغير مباشر على تكاليف تصنيع ونقل المواد إلى المواقع مما يؤثر بشكل إيجابي على التكلفة الإجمالية للمشاريع وكذلك يقلل من الأثر البيئي الضار المترتب على هذه المشاريع.

CHAPTER 1

INTRODUCTION

Concrete and other cementitious materials such as mortar and grout have been used for a long time in the construction industry due to their special properties which are mainly represented in their ability to be shaped easily along with their suitable mechanical properties for construction purposes, along with its low cost, making it the most commonly used composite material, where 30 billion tons of concrete is produced annually [1], [2]. These cementitious materials usually have high compressive strength, workability, and durability. Concrete is usually made by mixing Portland cement, freshwater, sand, and coarse aggregate to chemically react and form a paste that hardens later to be a rocklike material used in construction [3]. Concrete mortar is also usually made by mixing the same ingredients used in concrete except for the coarse aggregate. Normal concrete and mortar have a main flaw, which is its ability to resist tension where it has very weak tensile and flexural strengths [4]. Furthermore, cementitious materials tend to have high brittleness and low fracture toughness.

Cities' rapid development has a heavy demand for new infrastructures, mainly made of concrete [5]. The concrete industry, in turn, heavily relies on natural resources such as fresh water and river sand in addition to the extensive need to use steel with concrete as rebars to overcome concrete weaknesses. The huge demand for these natural materials could seriously threaten and directly affect the ecology of Earth and its natural resources [6], [7]

[8], [9]. Furthermore, in many cases, the usage of fresh water and normal sand in concrete significantly impacts the cost of the concrete since the transportation of the raw materials usually affects both the overall manufacturing cost of the concrete and the carbon footprint [10], [11]. As a matter of fact, a huge chunk of the annual carbon emissions is related to the concrete industry [7], [12]. Recently, the majority of sectors have heavily invested in developing eco-friendly materials and adapting low-footprint styles of manufacturing [13], [14].

Trying to solve a part of these problems, and to develop greener cementitious materials with less carbon footprint. Seawater and sea sand could be used in concrete mixes instead of freshwater and normal sand, reducing the high reliance on these limited materials and reducing the cost of raw materials transportation especially in remote coastal areas. However, in the case of steel-reinforced concrete, these alternatives introduce a problem, where the presence of ions in the seawater and sea sand could cause high corrosion to steel rebars reducing the age of reinforced concrete and reducing the area of steel in the structural section. Hence, glass fiber reinforced polymer (GFRP) along with basalt fibers (BF) can take the place of steel reinforcement in concrete, where basalt fiber could reduce shrinkage and enhance the tensile strength of concrete, and GFRP bars could compensate for the tensile forces in the structural element.

This research investigates the ability to reinforce seawater sea sand concrete (SSSC) and seawater sea sand mortar (SSSM) with different contents of chopped basalt fibers ranging from 0% to 1.5% producing basalt fiber reinforced seawater sea sand concrete (BFR-SSSC) and basalt fiber reinforced seawater sea sand mortar (BFR-SSSM). Studying their fresh

and hardened mechanical properties along with the microstructure of the hardened BFR-SSSC and BFR-SSSM.

For basalt fiber reinforced seawater sea sand concrete BFR-SSSC, workability is evaluated for each mix as per ASTM C143 concrete slump test [15]. During testing of workability, the results showed that the additional percentage of basalt fiber highly affects the workability of SSSC mixes, where the initial aim of reaching up to 2% basalt fiber content, shifted to 1.5% only for SSSC since the concrete mix almost completely loses its workability even with reaching the maximum superplasticizer allowed dosage. However, for SSSM basalt fiber content remained up to 2%. Compressive strength is also evaluated for both BFR-SSSC and BFR-SSSM as per ASTM C39 and ASTM C109 respectively. Casting six cylindrical concrete specimens for each mix at three different ages for BFR-SSSC, and 50x50x50 cubical mortar specimens for each mix at three different ages for BFR-SSSM. Results showed that adding basalt fibers slightly reduces the compressive strength of BFR-SSSC while slightly increasing it for BFR-SSSM. Observing the stress-strain curves of BFR-SSSC under compressive strength testing shows that the elastic modulus of concrete slightly increases with the additional amount of basalt fibers. Split tensile strength testing is done for BFR-SSSC as per ASTM C496 casting three cylindrical concrete specimens for each mix at three different ages, results showed that adding basalt fiber significantly enhances the flexural strength of SSSC despite the small reduction in compressive strength. Furthermore, the failure type of the specimens shifted from brittle to more ductile which indicates that the ductility in the concrete is increased with the additional dosage of basalt fiber. Flexural strength testing is done for both BFR-SSSC and BFR-SSSM as per ASTM C78 and ASTM C348 respectively casting beams for each mix

at three different ages, results showed that basalt fiber increased the flexural strength of both SSSC and SSSM significantly. During the flexural strength testing the load-deflection curve at the center of the specimens is also measured and the toughness is calculated where significant increase is observed in toughness for both SSSC and SSSM. To evaluate the durability aspects of concrete, water absorption of SSSC is also evaluated showing that basalt fibers enhance the durability performance of SSSC by decreasing its water absorption value. To measure the setting time of the BRF-SSSM, 5 patches of mortar are made each with different basalt fiber content, where each patch consists of 500g of cement, and the rest components are calculated according to the mix design stated earlier, where each patch is tested using setting time measuring device. Results showed that both initial and final setting times of SSSM are not significantly affected by the basalt fibers content. For drying shrinkage test, (25x25x285) mm prisms of mortar are made for each mix, where shrinkage is measured periodically, results showed that increasing basalt fiber content up to 2% significantly improves the SSSM resistance for drying shrinkage. In addition, scanning electron microscopy, energy dispersive X-ray spectroscopy, and X-ray diffraction analysis are done on BFR-SSSC and BRF-SSSM specimens to study the morphology and microstructure of the specimens. This study shows that the addition of basalt fiber (BF) to seawater sea sand concrete (SSSC) and seawater sea sand mortar (SSSM) significantly improves their mechanical, and durability properties, specifically the ones that are related to elasticity, without largely impacting their compressive strength while being resistant to corrosion. Therefore, this type of concrete and mortar can be applicable and feasible to be widely used especially for oil companies when constructing pipelines near remote shores

and in marine environments, which can directly affect the cost of raw materials transportation and solve other financial and logistical problems.

1.1 Research Significance and Novelty

Fresh water scarcity and concerns regarding exploitation of natural resources entail using alternative materials for concrete production. Therefore, seawater and sea sand have been proposed in this study and assess their feasibility for a stronger and more durable mortar and concrete. In addition, low cost and green basalt fibers were used to improve the mechanical behavior of the proposed composites, which has not been studied before.

CHAPTER 2

LITERATURE REVIEW

2.1 Basalt Fiber (BF)

A composite can be defined as a combination of two or more dissimilar materials used together as one material to perform a task that cannot be performed individually by either of these materials alone. Composites usually consisted of two main materials, which are preform, and matrix. The former acts as the reinforcing skeleton mainly made of fibers, and the latter acts as adhesive material binding the composite together and providing shape integration. One of the earliest composites used in recorded history, is the man-made bricks made of mud acting as Matrix, along with grass straws acting as Preform. Fiber reinforcement has been used for years to enhance the mechanical properties of materials. The most common types of fiber reinforcements used to make composites are carbon, aramid, glass, and basalt fibers [16].

Basalt Fiber or BF is a high-performance natural inorganic green material made out of natural basalt rocks, which are dark-colored igneous rocks known for their excellent thermal, strength, and durability properties. Furthermore, basalt fiber is considered a green industrial material since it is sustainable and recyclable, and no harmful or toxic chemicals are added during its manufacturing process [17]. In addition, the production of basalt fiber

uses significantly less energy than carbon fibers, glass fibers, and steel fibers. **Figure 1** shows the energy needed for the production of multiple types of fibers compared to basalt fibers [18], [19].

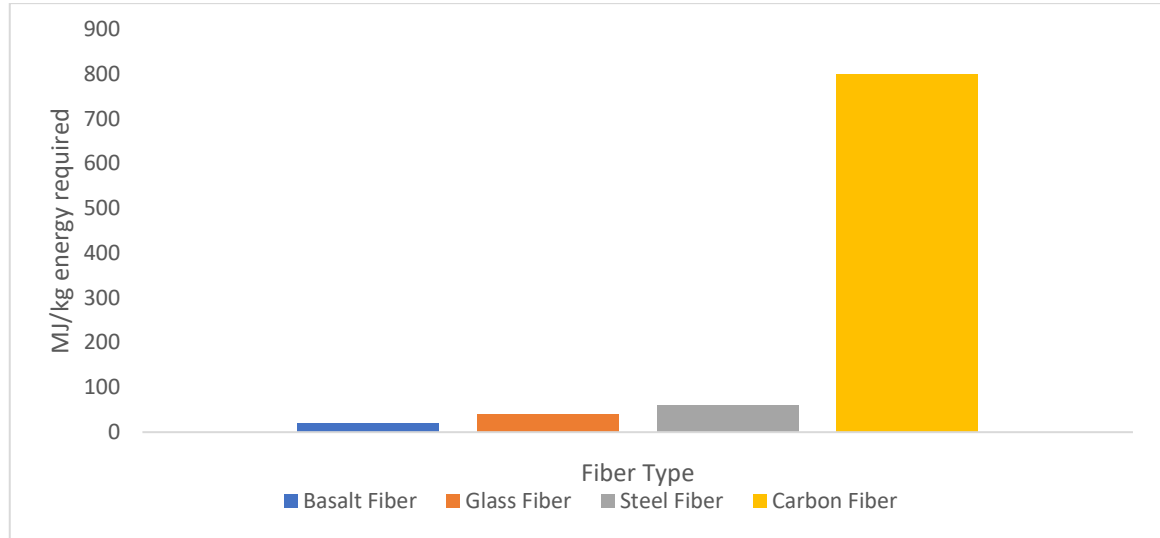


Figure 1 The energy required in MJ for manufacturing 1 kg of basalt, glass, steel, and carbon fibers [18] [19]. Basalt Fibers consist of a group of oxides, mainly SiO₂ as it dominates more than 50% of the basalt fiber content, followed by Al₂O₃, Fe₂O₃, FeO, CaO, and MgO respectively [20]. Basalt fiber has relatively similar chemical structure to glass fibers, however, it has better mechanical properties and better chemical resistance. In addition, it costs less than glass fiber and other fibers and is easier to process [21], [22]. In comparison with steel fibers, basalt fiber has less weight and has better resistance to rust [23]. **Table 1** shows the different mechanical properties of basalt in comparison with other fibers.

Table 1 Mechanical properties comparison [24].

Fiber	Density	Tensile Strength	Elastic Modulus	Elongation at Break
	(g/cm ³)	(GPa)	(GPa)	(%)
Carbon	1.4	4.0	230-240	1.4-1.8
Basalt	2.8	2.8 – 4.8 [10]	89	3.15
E-glass	2.56	1.4-2.5	76	1.8-3.2
Flax	1.5	0.5-1.5	27.6	2.7-3.2

Table 1 shows that basalt has better mechanical properties compared to glass fibers. However, even though carbon has superior properties in almost every aspect; its high cost compared to basalt fiber could play a significant role in its usage as a pre-form in the concrete matrix. Based on the good properties of basalt fiber, such as its high mechanical properties, and its excellent resistance to corrosion along with other properties such as high melting point and insulation, it found its way too many different industries including the construction industry, especially as reinforcing fiber to the concrete to overcome its weakness points such as shrinkage, low tensile strength, flexural strength, and brittleness. Furthermore, basalt fiber is vibration-resistant compared to other similar products where it has very high energy absorption capacity [25], so it is used to enhance the concrete ability to resist vibrations. The composite of basalt fibers BF acting as preform and the concrete acting as a matrix is called basalt fiber reinforced concrete or BFRC [26].

Basalt fiber reinforced concrete (BFRC) mechanical properties can be largely altered by the ratio of fiber content in the matrix and by its volume fraction. Studies showed that increasing fiber content decreases the workability of concrete. Furthermore, to achieve the highest possible compressive strength for the fibers, the optimum volume fraction of BF should be around 2%, and when the volume fraction of fibers increases, the concrete strength increases [18]. Others studied the BFRC compressive, tensile, and flexural strengths and observed that to achieve optimum strength; basalt fiber should be within 0.3% - 0.5% volume fraction, have 6-16mm length, and 10-20 μm diameter [27]. Furthermore, a study investigated the mechanical properties of BFRC for different BF volumes and different aggregate types, the study showed that BF optimum volume

percentage is 1% to achieve the best compressive, tensile, and flexural strengths, where **Figure 1** shows the study results [28].

Basalt fiber is found to be greatly beneficial when used in concrete in any form including rebars, meshes, or chopped fibers, where basalt fiber enhances the toughness, energy absorption, bending properties, and tensile, and bond strength of concrete. The previously mentioned properties are found to increase with the increase of basalt fiber volume until they reach a certain point where any additional amount of fiber could decrease the concrete properties. It is found that BFRP bars relationship with the flexural strength of the reinforced concrete depends on the diameter, spacing, and texture of the bars, where the bars with larger diameter perform better regarding load capacity of the section, and smaller diameter bars perform better regarding bonding strength. Furthermore, thanks to the elasticity of BFRP bars, they tend to have elastic deformation similar to steel rebars, and unlike other FRP bars. Basalt fiber was found to have a unique and astonishing ability to absorb energy, allowing it to be used in various sectors, especially against blast or impact loading. Regarding the microscopic properties of basalt fibers, **Figure 2** [29] show that the basalt fibers have smooth surfaces with no cracks, cavities, or notches.

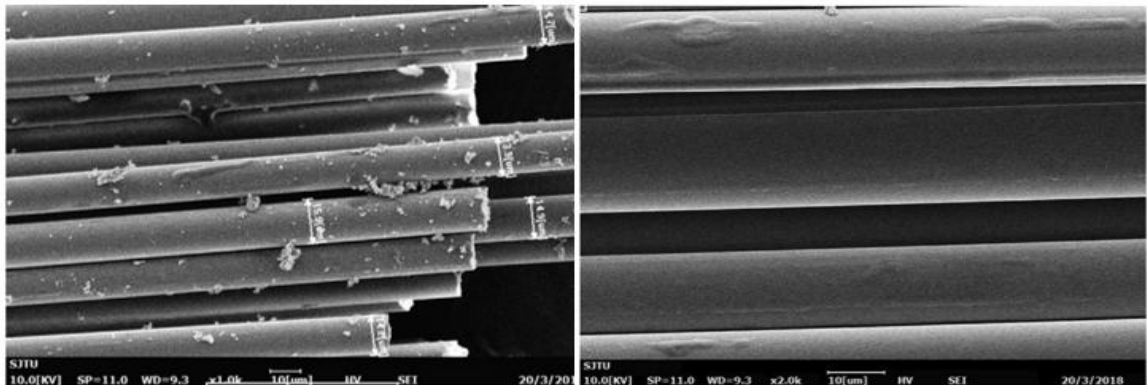


Figure 2 Basalt fibers 10-micrometer scale SEM images.

2.2 Basalt Fiber Reinforced Concrete (BFRC)

Cement composites are mainly used as either mortar or concrete, where the former consists of cement, water, and fine aggregate, while the latter consists of the same combination of mortar along coarse aggregate. Usually, concrete is used along with reinforcing bars to create load-bearing structural elements that can withstand large actions such as columns, beams, and slabs due to their higher compressive strength. While mortar is usually used for non-structural applications mainly as binding material for bricks or finishing purposes. Both concrete and mortar composites have relatively high compressive strength, but low tensile and flexural strengths.

Although concrete and mortar have similar low tensile and flexural strength, they have comparatively high compressive strength. In addition, they have weak resistance to impact, suffering from micro-cracks in the matrix weakening their overall performance. To overcome these problems, researchers have studied the feasibility of adding different fibers to reinforce these composites and they found that fiber additions bridge the microcracks of the cement composites thus enhancing the overall performance of cement composite increasing their toughness against fractures, and improving their flexural behavior [30] [31]. Studies are conducted regarding using the basalt fibers with concrete and mortar, and found that depending on the volume fraction V_f , and properties of BF, the compressive strength of concrete can be slightly decreased by the additional BF, however, the tensile and flexural strength of concrete can be enhanced along with the increase in section ductility [32]. Studies showed that using basalt fiber in concrete structures can enhance the resistance of weathering of concrete compared to glass fiber [33].

Studies conducted on the fresh properties of basalt fiber reinforced concrete (BFRC) found that basalt fiber content affects the setting time of concrete, where a 10% basalt fiber content can increase the initial setting time of concrete by between 30.2% and 31.2% depending on the length of basalt fibers, and can increase the final setting time 27.75% in average [34]. The effect of BF on the workability of BFRC is also found to be significant, where additional BF content can significantly affect the measured slump of concrete [35] [36]. Researchers also explored the mechanical properties of basalt fiber cementitious composites for various applications where the addition of basalt fiber in concrete showed enhancement to the impact resistance of concrete under loading conditions [37]. Furthermore, it is found that the splitting tensile strength of concrete can be highly improved with higher basalt fiber dosages [38]. Studies also investigated the use of chopped basalt fiber additives to improve the mechanical properties of concrete, where the mechanical properties of concrete including different types of concrete shown to be affected, and the overall performance of various types of concrete was shown to be affected by adding basalt fibers [39], [40], [41].

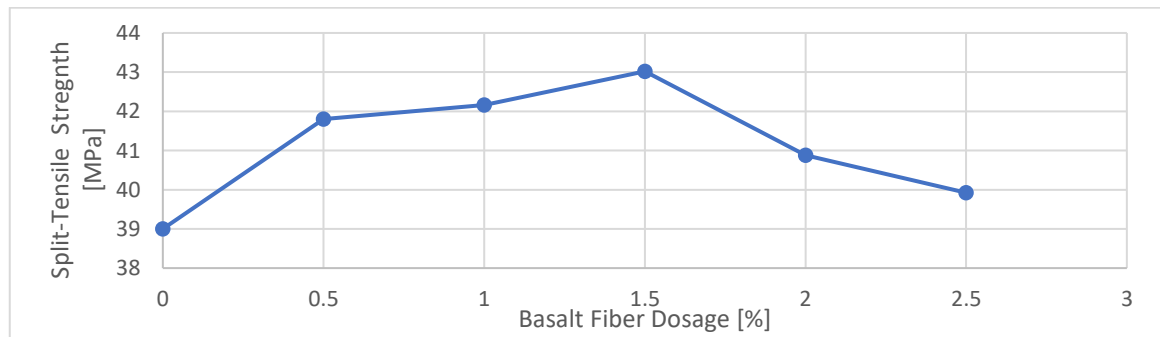


Figure 3 Split-tensile strength of concrete vs BF content [36].

The compressive strength of concrete was found to be increasing slightly with the addition of BF content up to 2% volume [36]. Another study on compressive strength stated that the

effect of basalt fiber on the compressive strength of concrete is negligible up to 1.5% volume [28].

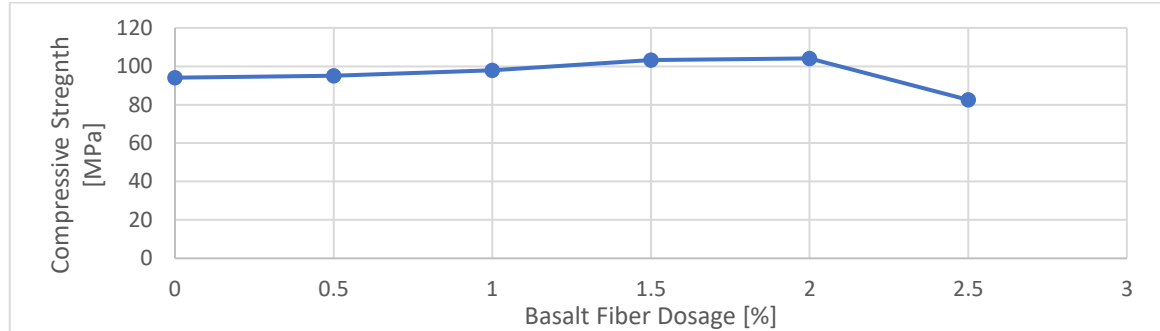


Figure 4 Compressive strength of concrete vs BF content [36].

The modulus of elasticity of concrete has been studied by several researchers, where researchers found that the modulus of elasticity is decreased when basalt fiber is added to the mix [38], [42].

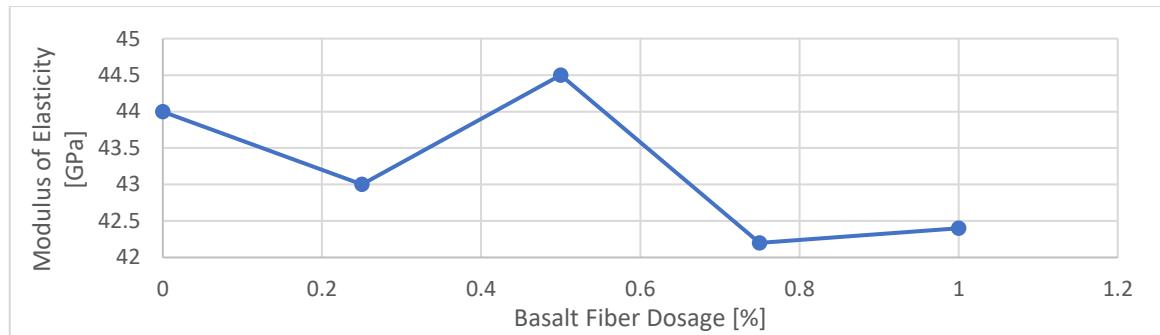


Figure 5 Modulus of elasticity of concrete vs BF content [38].

2.3 Basalt Fiber Reinforced Mortar (BFRM)

Basalt fiber reinforced mortar has also been studied by multiple researchers. However, it has less literature than basalt fiber reinforced concrete. [43] evaluated the influence of basalt fiber on the performance of cement mortar where the shrinkage and mechanical properties are studied, the study shows that the shrinkage of cement mortar is significantly reduced when basalt fibers are added to the mix. **Figure 6** shows the shrinkage of mortar

with BF at 28 days according to [43]. [44] stated that there is always an increase in flexural strength and flexural modulus in cement mortar when basalt fibers are added to the mix. In a study on mortar where the strain of basalt fiber-reinforced mortar is investigated, it is found that the additional basalt fiber content causes a bridging effect resulting in more elasticity in the mortar and ductility, along with increasing its toughness compared to plain mortar, also it shows enhancement in the tensile strength of mortar [45]. Basalt fiber reinforced mortar has also been evaluated for durability under freeze-thaw and chloride-rich environments, with an optimized fiber content proposed to enhance the durability of the mortar, addition basalt fiber content showed significant improvement to the durability of mortar, and compressive strength of mortar slightly increased to a certain limit when basalt fiber is used in the mortar [46].

Basalt fibers' effect on the process of compressive failure of mortar has been investigated, with studies focusing on the impact of basalt fiber content on acoustic emission characteristics during the damage process, where the damage mechanism of basalt fiber-reinforced mortar under axial compression is analyzed, and studied, where it is stated that the basalt fibers addition can enhance both ductility and rigidity of the mortar [47].

Additionally, the durability of basalt fiber-reinforced mortars exposed to high temperatures has been investigated, showing that basalt fiber mortar exposed to high temperatures has higher residual durability compared to plain mortar, where basalt fibers tend to bridge the cracks preventing mortar from cracking under high temperatures [48].

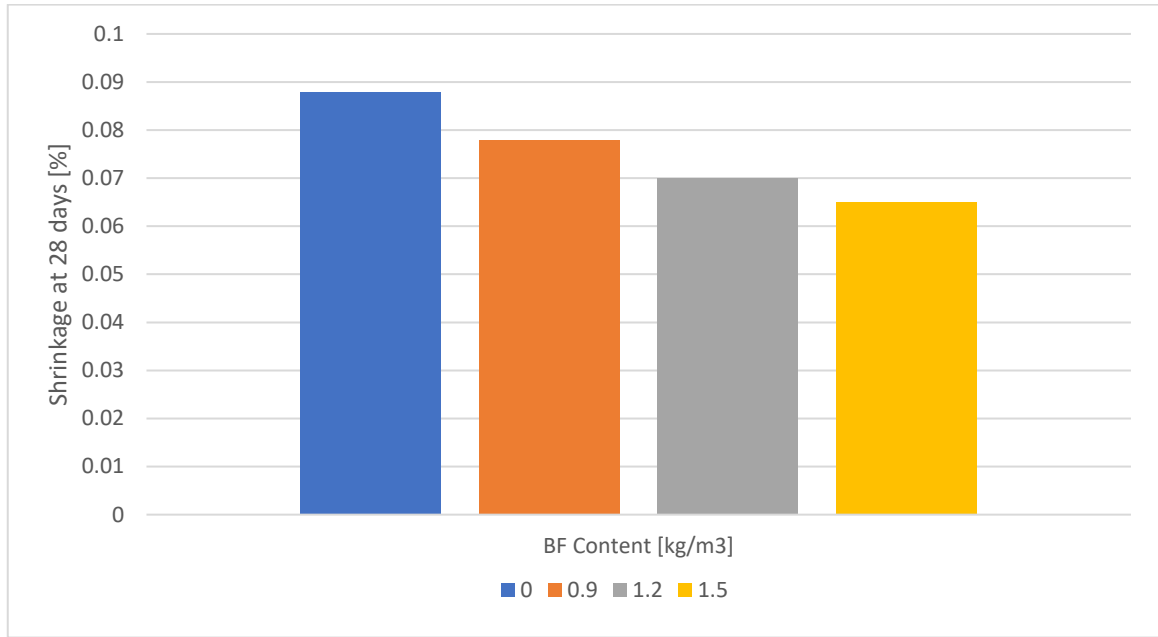


Figure 6 Shrinkage ratio of BFRM at 28 days [43].

2.4 Seawater

According to Nacional Ocean Services [49], around 71% of the Earth's surface is covered by seawater, and around 97% of the Earth's water can be found as seawater. which makes it very accessible and cheap-to-use material. Sea water is a complex mixture of dissolved salts, minerals, gasses, and organic materials. It contains a variety of ions from the weathering of rocks and trace elements that are vital to marine life, with an average salinity of roughly 3.5% overall, or $S_R = 35\text{g/kg}$ [50]. Because seawater contains salt, its density, freezing point, and boiling point are different from those of freshwater [51]. Seawater contains so many ions, however, the main ions that are present in large quantities in seawater are Chloride, Sodium, Sulfate, and Magnesium. **Table 2** shows the concentrations of 99.9% of the ions usually present in seawater.

Table 2 Average concentrations of 99.9% of the ions present in seawater [52].

chemical ion	concentration	part of salinity	Molecular weight
	[mg/kg]	[%]	
Chloride Cl	19345	55.03	35.453
Sodium Na	10752	30.59	22.990
Sulfate SO ₄	2701	7.68	96.062
Magnesium Mg	1295	3.68	24.305
Calcium Ca	416	1.18	40.078
Potassium K	390	1.11	39.098
Bicarbonate HCO ₃	145	0.41	61.016
Bromide Br	66	0.19	79.904
Borate BO ₃	27	0.08	58.808
Strontium Sr	13	0.04	87.620
Fluoride F	1	0.003	18.998

Arabic Gulf seawater contains a particular salt content that adds to its unique qualities. The majority of the dissolved salts in saltwater are made up mostly of sodium and chloride ions. But the quantities of other ions, like potassium, calcium, and magnesium, are also higher in the Arabian Gulf. Several variables, including geological processes, hydrological inputs from nearby rivers, and human activity, have an impact on these fluctuations in ion composition. The salinity of the Arabian Gulf is significantly higher than the average seawater salinity and the standard seawater salinity, and its salinity is rising over time [53], [54]. Seawater's salinity, generally stated as parts per thousand (ppt) or practical salinity

units (PSU), is primarily used to measure the salt concentration in the water. Salinity levels in the Arabian Gulf are noticeably higher than those in other global waters. The Arabian Gulf's salt levels have been found to range from 37 to 41 ppt in numerous studies, which is much higher than the average salinity of about 35 ppt worldwide. The region's high evaporation rates, restricted freshwater inflow, and arid environment are the main causes of the heightened salinity. **Table 3** shows the salt concentration in (ppt) and the dominant ions in multiple seas according to several studies [40], [41], [42], [43].

Table 3 Salt concentration in different seas [40], [41], [42], [43].

Sea	Salt Concentration (ppt)	Dominant Ions
Arabian Gulf	37-41	(Na ⁺), (Cl ⁻)
North Atlantic Ocean	35	(Na ⁺), (Cl ⁻)
Mediterranean Sea	38	(Na ⁺), (Cl ⁻)
Red Sea	40-42	(Na ⁺), (Cl ⁻)
Baltic Sea	6-8	(Na ⁺), (Cl ⁻)
South China Sea	32-35	(Na ⁺), (Cl ⁻)
Indian Ocean	33-37	(Na ⁺), (Cl ⁻)
Pacific Ocean	33-37	(Na ⁺), (Cl ⁻)
Arctic Ocean	30-34	(Na ⁺), (Cl ⁻)
Black Sea	17-22	(Na ⁺), (Cl ⁻), (SO ₄ ²⁻)

Based on the literature, ion concentrations vary depending on the location of seawater. **Table 4** shows this difference in ions concentration. Mostly, Chloride ions are the dominant ions in seawater, followed by sulfate ions, magnesium ions, and calcium ions respectively [56].

Table 4 Salt content of seawater at different locations.

Location	Salt Content (mg/L)				Total Salt Content (mg/L)	Reference
	SO ₄ ²⁻	Mg ²⁺	Cl ⁻	Ca ²⁺		
Qatar	2359	-	18600	-	30300	[57]
Spain	2820	1360	20800	490	-	[58]
Australia	3420	1430	20700	-	-	[59]
China - Shenzhen	1820	1000	20000	395	-	[60]
China - Qingdao	2400	1445	16000	-	29040	[61]
China - Penglai	2169	1093	15775	384	28503	[61]

2.5 Sea Sand

Sea sand is an important coastal resource, it has characteristics that set it apart from other types of sand including particle size, composition, hardness, hardness, and stiffness. Comprehending these characteristics is essential to understand the applicability of this material in different sectors. Focusing here on the sea sand application in SSSC and SSSM. Research has been done into studying the distribution of sea sand particle size, where it is found that generally, sea sand has a grain size distribution between 0.0625mm to 2mm, which can be affected by the area of sea sand. Wave action, sediment movement, and heat influence the grain size of sea sand. Sea sand mainly consists of silica in the form of quartz crystals. In addition to silica, sea sand can have mica, feldspar, and organic substances in its composition depending on the coastal region from which the sea sand is extracted [62], [63]. Sea sand properties differ greatly in literature, depending on many reasons including climate zones where the sand originally resided [64], [65].

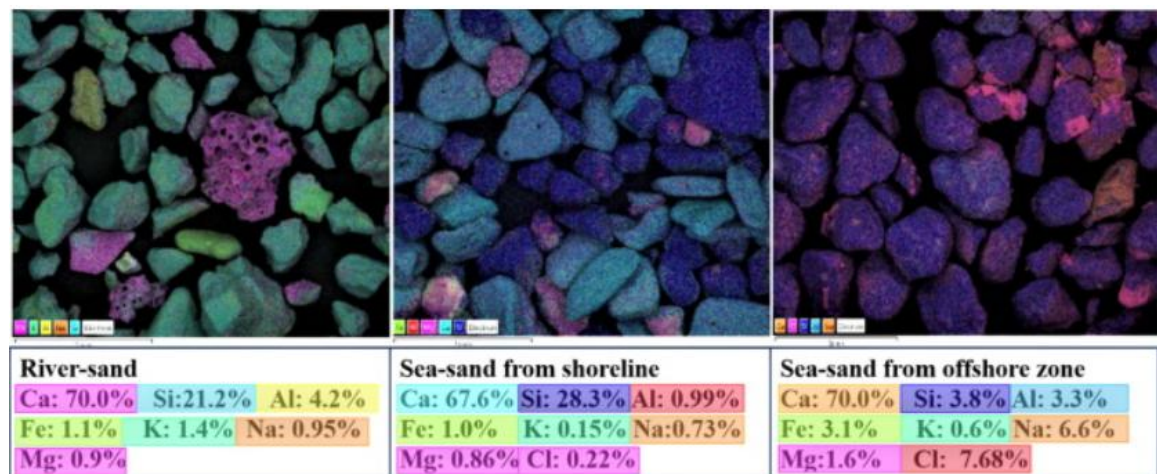


Figure 7 SEM-MEC different types of sand [66].

Figure 7 shows the different elemental compositions of several types of sand, where it is observed that sand composition can be significantly different from one zone to another [66]. The same study compared the mineral composition of sea sand to river sand using XRD and found that they share their mineral composition and geological origin [66], [67]. **Figure 8** shows that sea sand and river sand generate similar phase angles where quartz and feldspar are the main components.

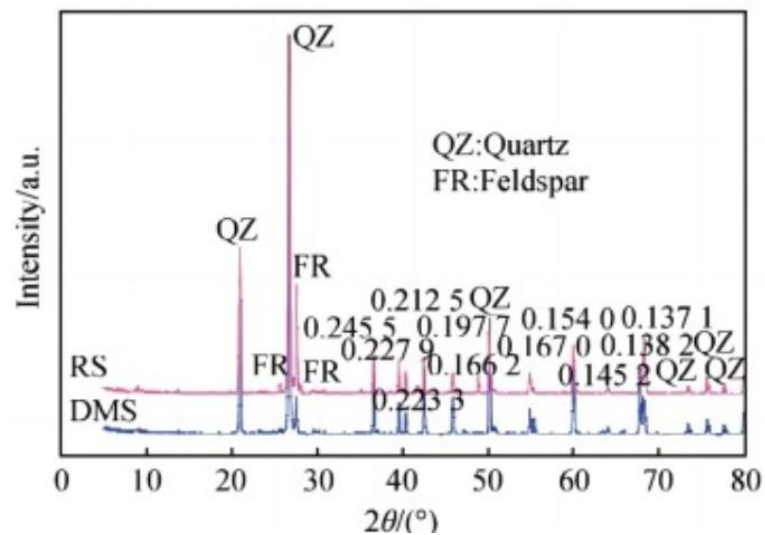


Figure 8 XRD spectra of river sand and sea sand [67].

Sea sand composition differs depending on its extraction area, where many aspects such as Chloride, organic, and clay contents. In addition, sea sand have larger content of chloride and shell compared to normal sand [56]. **Figure 9** shows the differences in three aspects of sea sand depending on its extraction location.

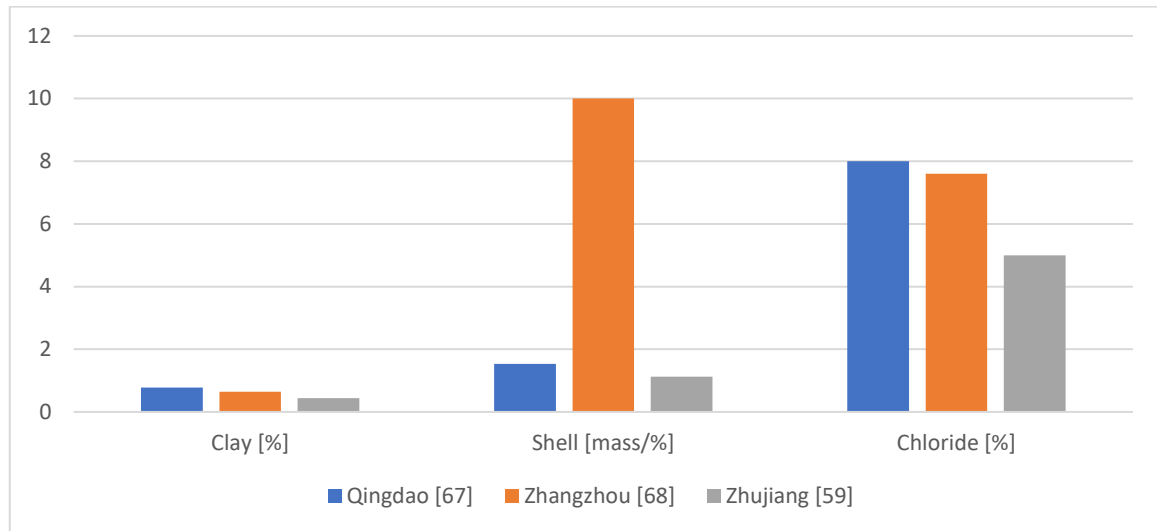


Figure 9 Different aspects of sea sand at Qingdao [68], Zhangzhou [69], Zhujiang [60].

2.6 Seawater Concrete and Seawater Sea Sand Concrete (SSSC)

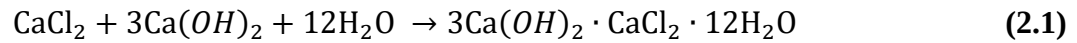
The scarcity of freshwater and river sand in coastal regions encourages research on using seawater sea sand concrete (SSSC) and seawater concrete [65], [71], [72]. Seawater sea sand concrete (SSSC) can be identified as a concrete mix that uses seawater and sea sand instead of freshwater and river sand or normal sand, and seawater concrete is a concrete mix that uses seawater as mixing water instead of freshwater. In this section, the studies conducted on seawater concrete and seawater sea sand concrete will be shown respectively.

2.6.1 Seawater Concrete

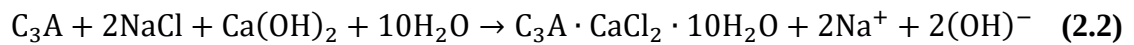
Studies conducted on concrete mixed with seawater only showed that the workability of concrete can be affected when seawater is used as mixing water, where a 20% reduction in initial slump is reported. In addition, when seawater is used in the mix, a 30% loss in the initial setting time is reported [57], [73]. Furthermore, studies showed that seawater can increase the early strength of concrete within the first 14 days by up to 25%, however, it

does not affect the absolute concrete strength significantly [57], [73], [74]. Also, seawater as mixing water was found to reduce the drying shrinkage of concrete significantly [75].

The presence of different ions in the seawater such as chloride, sodium, and magnesium ions are introduced to the concrete mix when seawater is used as mixing water, altering the hydration process of concrete and thus affecting the previously mentioned properties of concrete. As shown in **Eq. (2.1)** calcium hydroxide (CH) which is normally formed in the hydration process of cement and calcium chloride (CaCl₂) which is present because of seawater in the mix, react with each other forming calcium oxychloride (CAOXY) which is a solid insoluble phase [76].

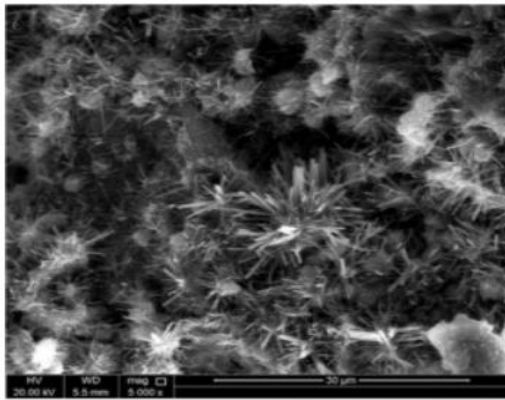


This reaction consumes the calcium reducing the alkalinity and calcium concentrations in the solution, promoting the dissolution of cement particles, thus, accelerating the hydration rate. Furthermore, chloride ions react with different hydrates of cement hydration, mainly tricalcium aluminates (C₃A) and tricalcium aluminoferrite (C₄AF), commonly known as aluminates and ferrites respectively [77], [78], producing insoluble phase [79], as illustrated in **Eq. (2.2)**.

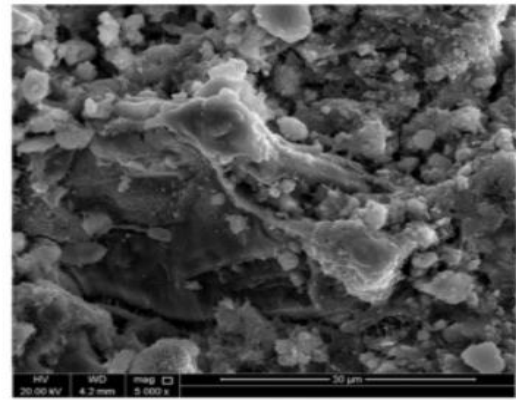


The production of this chemical reaction is known as Freidel's salt [80] which belongs to (AFm phase) family. Freidel's salt densifies the cement matrix and changes the concentrations of sulfate and chloride ions [81], [82]. This densification of concrete encouraged by the presence of seawater can be shown in **Figure 10** where the seawater cement paste shows more organized ettringite, and closely packed portlandite compared to

freshwater cement paste where pores are not filled properly with portlandite, and the crystals are poorly arranged. Furthermore, the C-S-H matrix of seawater concrete showed to be more compact and well-filled by Friedel's salt and ettringite [83], [84], [85]. **Figure 11** is a nano-scale TEM image of the C-S-H matrix phase produced in seawater and freshwater samples at 28 days of curing age.

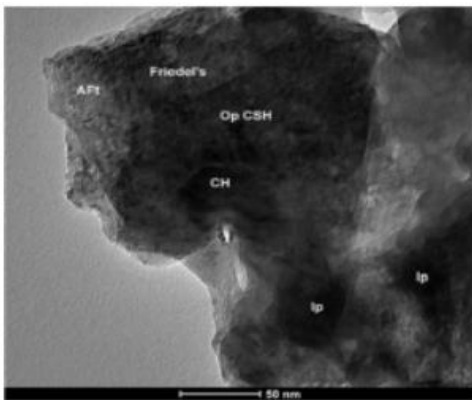


(a) 3-day freshwater paste

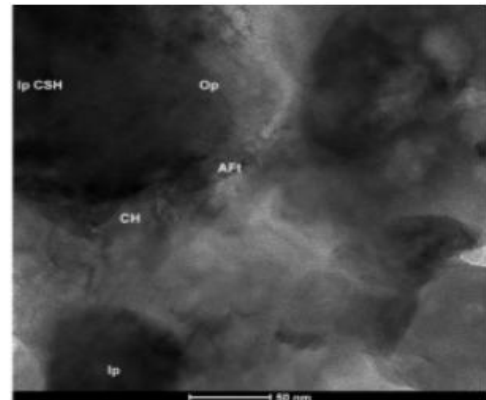


(b) 3-day seawater paste

Figure 10 SE image for 3-day cement paste (a) freshwater paste (b) seawater paste [57].



(a) Seawater



(b) Freshwater

Figure 11 TEM image of C-S-H matrix phase of cement paste (a) seawater (b) freshwater [85].

In general, the majority of studies showed that using seawater as mixing water for concrete does not meaningfully harm the integrity of concrete, at the same time it is revealed that compressive strength, elastic modulus, density, and durability of concrete can be improved when seawater is used as mixing water for concrete [57], [58], [64], [73], [86]. A study

conducted a study on concrete made with seawater and un-washed sea sand showed that the compressive strength of concrete is higher when seawater and sea sand are used in the mix instead of fresh water and normal sand, furthermore, the density of concrete made with seawater and sea sand showed higher density, **Figure 12** shows the difference in compressive strength obtained by the study [75].

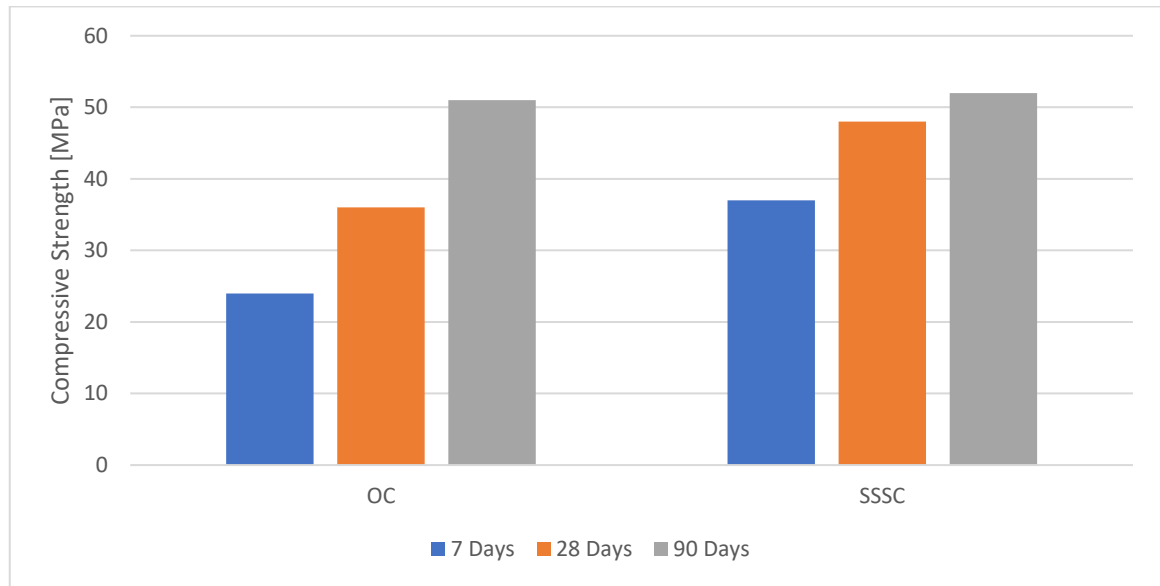


Figure 12 Compressive strength differences between ordinary concrete and SSSC [75].

2.6.2 Seawater Sea Sand Concrete (SSSC)

Much research is done on SSSC where different aspects of SSSC have been studied. Studies showed that replacing river sand with sea sand affects the workability by decreasing it, whereas using sea sand with its relatively high water absorption value requires more water in the mix, in addition to the presence of shells in the sea sand also affects the workability of concrete mixes [87], [88], [89]. Generally, the compressive strength of SSSC showed to develop higher early compressive strength compared to normal concrete mixes due to the hydration acceleration effect, with lower late compressive strength. However, the difference in compressive strength is not significant. Between 13%

to 60% increase in early compressive strength and between 1.8% to 7.7% decrease in late compressive strength are reported [90], [91], [92], [93]. **Figure 13** shows the average compressive strength of SSSC compared to normal concrete for different ages.

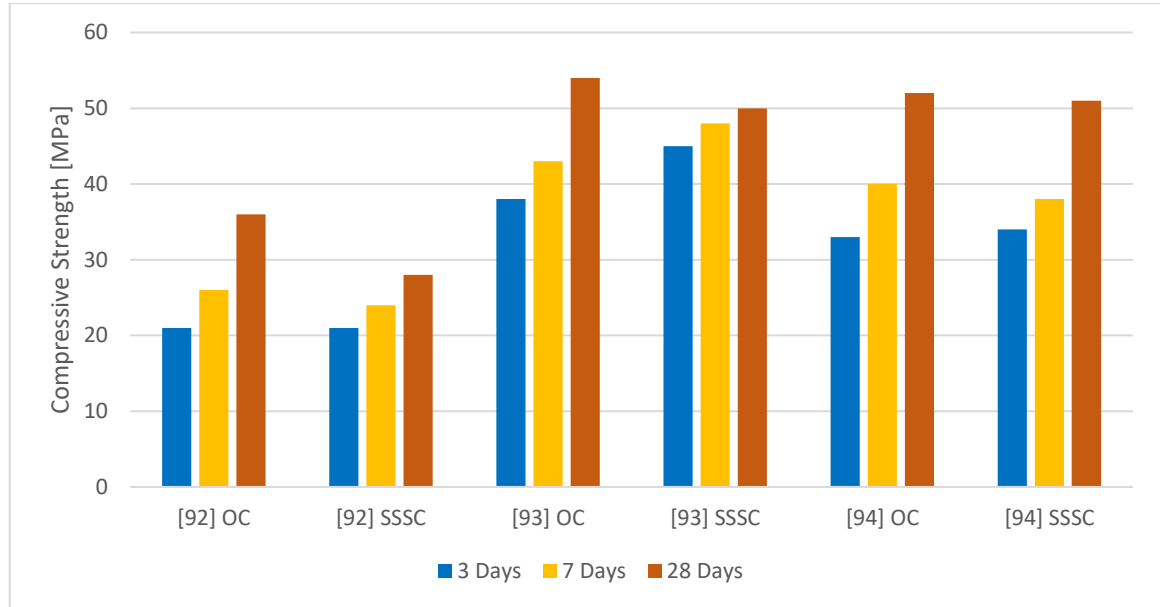


Figure 13 Compressive strength values for SSSC and ordinary concrete [94], [95], [96].

The presence of chloride ions in sea sand and seawater alters the hydration process of concrete where calcium oxychloride (CAOXY) is formed as a solid insoluble phase as mentioned in **Eq. (2.1)** [76]. Calcium is consumed during this reaction, and as a result, alkalinity and calcium concentrations are reduced in the solution, which promotes the dissolution of cement particles and accelerates the hydration rate. Furthermore, chloride ions react with aluminates and ferrites producing Freidel's salt, as illustrated in **Eq. (2.2)**. [77], [78], [79]. Freidel's salt makes the cement matrix more dense and changes the concentrations of sulfate and chloride ions [81], [82]. This densification of SSSC is shown in **Figures 14,15,16**, where SEM is done on seawater sea sand concrete (SSSC) and ordinary concrete (OC) where the surface morphology of ordinary concrete made with freshwater and river sand is shown to be less developed compared to SSSC. The ettringite

phase in SSSC showed more developed crystal formation compared to OC with leads to a more dense structure [90], [92]. (C-S-H) also showed to be heavier and densier in SSSC compared to OC [92].

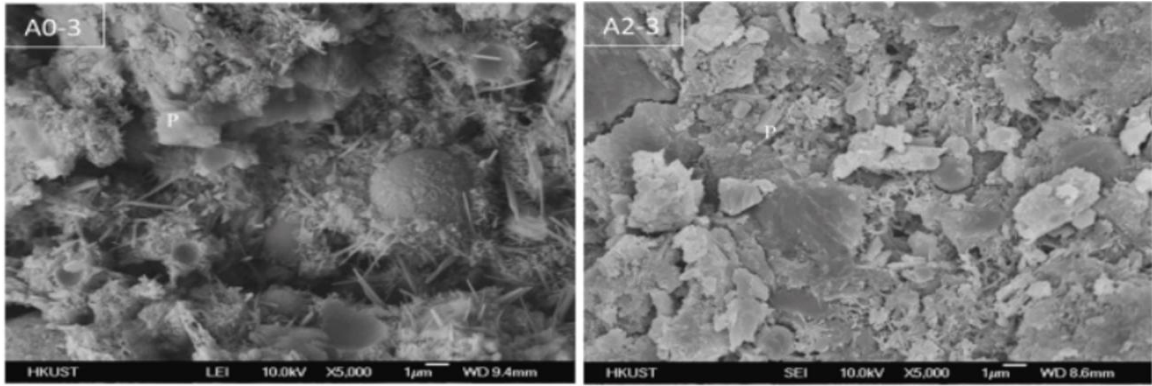


Figure 14 SEM of SSSC and OC at 3-day age [92]. A0 = OC; A2 = SSSC; P = CH.

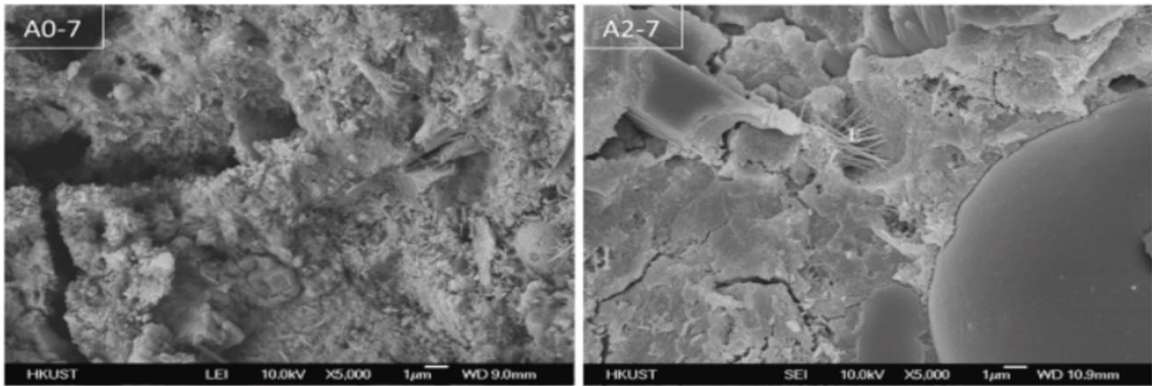


Figure 15 SEM of SSSC and OC at 7-day age [92]. A0 = OC; A2 = SSSC; E = Ettringite.

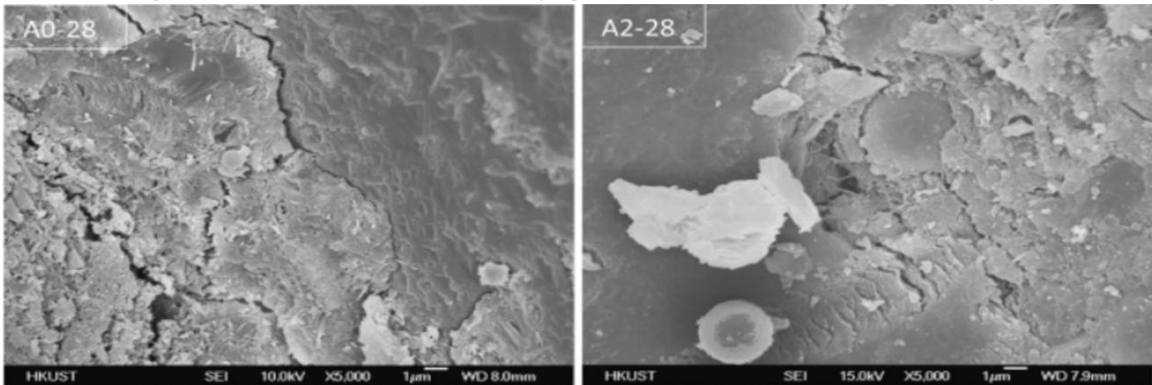


Figure 16 SEM of SSSC and OC at 28-day age [92]. A0 = OC; A2 = SSSC; E = Ettringite.

Flexural strength of SSSC was reported to be higher than that in OC by 18.2% [92] related to the increase of SSSC density due to the presence of chloride [57], [64]. SSSC also showed significantly reduced permeability compared to OC [64], [75], [97]. In addition,

SSSC was reported to have lower chloride permeability when exposed to external chloride due to the fact that reduced chloride concentration gradient between pore solution and external solution [65], [98].

2.7 Seawater Sea Sand Mortar (SSSM)

SSSM is another cementitious composite that uses seawater and sea sand as mixing materials instead of seawater and sea sand. Multiple studies are conducted to determine its different aspects and applications. A study conducted on mortar made with seawater and un-washed sea sand showed that the compressive strength of mortar is higher when seawater and sea sand are used in the mix instead of fresh water and normal sand. **Figure 17** shows the difference in compressive strength obtained by the study [75].

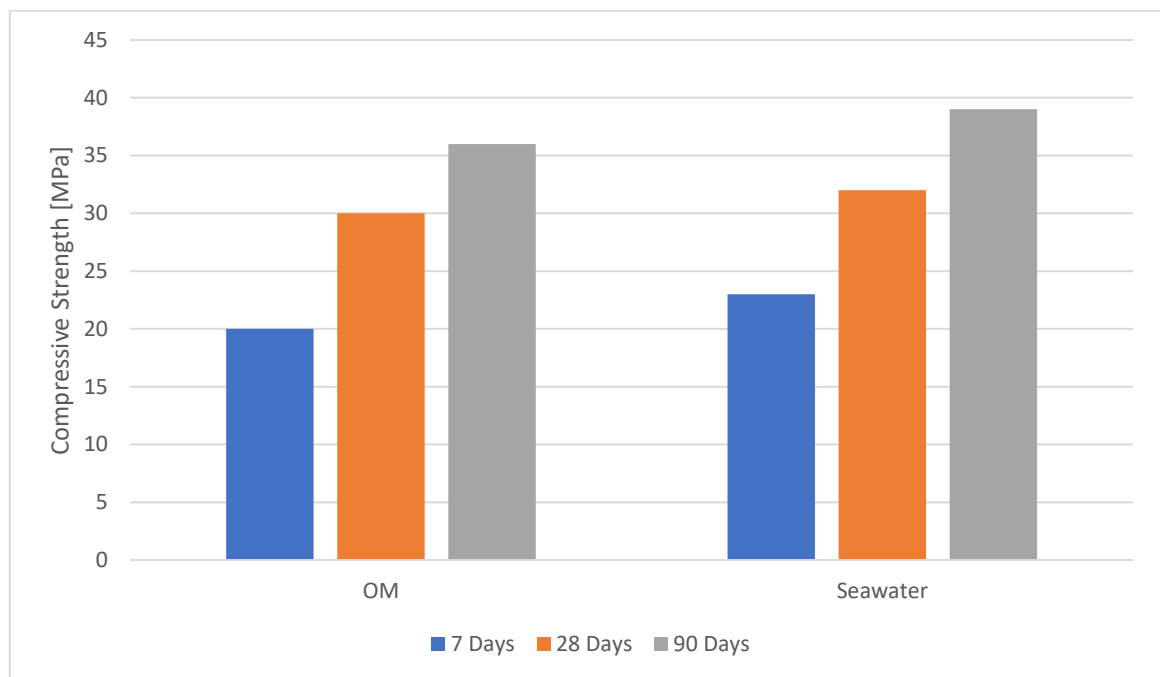


Figure 17 Compressive strength differences between ordinary mortar and SSSC [75].

However, the compressive strength of concrete is reported differently through the literature, where it ranges from a 46% reduction in compressive strength up to a 60% increase in compressive strength [75], [88], [96], [99].

CHAPTER 3

METHODOLOGY

3.1 Materials and their characteristics.

3.1.1 Cement.

Ordinary Portland Cement (OPC) produced by Qassim Cement complies with ASTM C150-92, SASO-GSO 1914/2009 (Type I) with a specific gravity of 3.15 (g/cc). *Contents are provided by the supplier.*

3.1.2 Mixing Water.

Natural surface seawater (collected from Halfmoon Beach on the east coast of Saudi Arabia - Arab Gulf). Different ion concentrations are found by analyzing the seawater with different methods including Ion Selective Electrode (ISE) an analytical method that measures the electrical potential to evaluate the activity of chloride ions in an aqueous solution, Turbidimetric Determination where the sulfate ions present in the sample are converted into a suspension of barium sulfate which is then determined turbidimetrically, and Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) a method that uses plasma and a spectrometer to analyze the composition of dissolved elements in water samples. The concentration of ions, and analysis types, are presented in **Table 5**.

Table 5 Ion concentrations in seawater used in the experiment.

Characteristic	Analysis	Value (mg/kg)
Chloride	(ISE)	33755
Sulfate	(Turbidimetric Determination)	3238
Calcium	(ICP-OES)	432.6
Magnesium	(ICP-OES)	2500.3
Potassium	(ICP-OES)	856.1
Sodium	(ICP-OES)	14304

According to ASTM C1602 the maximum limit for concentration of sulfate in mixing water of concrete is 3000 mg/L and the maximum water-soluble chloride ion content in concrete percent by weight of cement is 1% for dry reinforced concrete that is protected from moisture in service [100]. Seawater that is used in this experiment have 3238 mg/L sulphate content and 33755 mg/L chloride ion content which translates to 1.69% to the weight of cement since 0.5 W/C ratio is used. However, even though these numbers exceed the stated limits, they are to be ignored since the purpose of using such concrete mix is to be used with non-metallic reinforcement such as BFRP and GFRP which are corrosion-resisting composite materials.

3.1.3 Sand

Un-washed sea sand (collected from Halfmoon Beach on the east coast of Saudi Arabia - Arab Gulf), contains a few impurities such as sea salt. Different characterization tests are done on the sand to obtain its characteristics including specific gravity, moisture content, water absorption, and sieve analysis. The values of each test are listed in **Table 6**.

Table 6 Sea sand characteristics.

Characteristic	Value
Specific gravity	2.63
Moisture content	5.17 %
Water absorption	6.07 %
Fineness modulus	1.68 Zone 4



Figure 18 Sea sand is used in the mix as fine aggregate.



Figure 19 Halfmoon Beach - Saudi Arabia. The location where seawater and sea sand samples are collected.



Figure 20 Characterization of sea sand.

Table 7 shows the sieve analysis of sea sand where the total sample size of sand is 1000 g and the fineness modulus is calculated to be 1.68 which lays in zone 4 of sand fineness classification. Following **Figure 21** shows the particle size distribution of sea sand where more sieve sizes are used in this analysis to obtain higher accuracy.

Table 7 Sieve analysis of the sea sand used in the experiment.

Sieve Number	Diameter (mm)	Soil Mass Retained (g)	Cumulative mass retained (g)	Cumulative mass retained (%)
4	4.750	0.07	0.07	0.007
10	2.000	0.02	0.09	0.009
16	1.180	0.1	0.19	0.019
30	0.600	28.6	28.79	2.879
50	0.300	623.28	652.07	65.207
100	0.150	341.66	993.73	99.373
Pan	0.000	6.27	1000	100

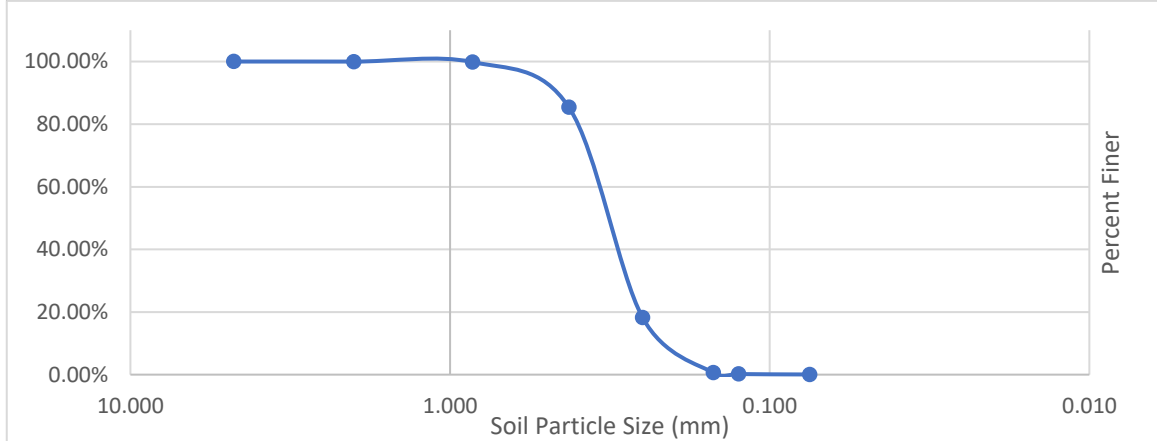


Figure 21 Particle size distribution of sea sand.

3.1.4 Coarse aggregate (3/4) and (3/8).

Basalt coarse aggregate is used in the mix, which is obtained from the Qassim region in Saudi Arabia, Characteristics of both (3/4) and (3/8) coarse aggregate are done to find their specific gravity, moisture content, water absorption, and sieve analysis. The values of each test for both (3/4) and (3/8) coarse aggregate are listed in **Table 8**.

Table 8 Coarse aggregate Characteristics.

Characteristic	Value (3/4)	Value (3/8)
Specific gravity	2.81	2.79
Moisture content	0.45%	0.45%
Water absorption	0.49%	0.49%

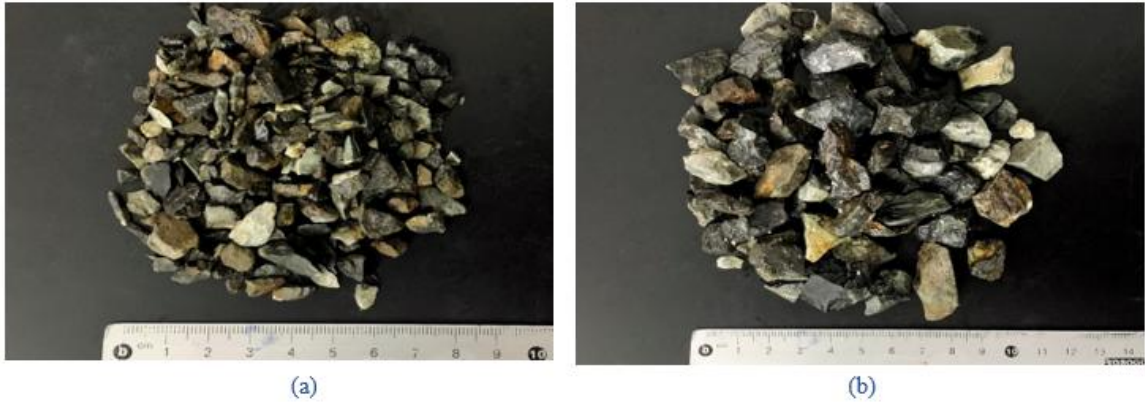


Figure 22 Coarse aggregate. (a) 3/8 Basalt coarse aggregate. (b) 3/4 basalt coarse aggregate.

3.1.5 Basalt Fiber.

Basalt fiber is the main focal point of this experiment where it is obtained from Russia as a monofilament of 0.013 mm diameter, and 12.7 mm length (aspect ratio: 976). With an SG of 2.40 (g/cc), moisture content < 0.1%. with a tensile strength of 1735 MPa. The properties of basalt fiber are listed in **Table 9**.

Table 9 Properties of basalt fiber.

Length	Diameter	Density	Tensile Strength	Water Absorption
[mm]	[mm]	[g/cc]	[MPa]	-
12.7	0.013	2.40	1735	0.25



Figure 23 basalt fiber used in the mix.

3.1.6 Superplasticizer.

Since basalt fiber has high water absorption, the need for a superplasticizer as an admixture is present, so it is used in the mix where the characteristics of the chemical admixture are provided by the manufacturer as shown in **Table 10**.

The material is named Hyperplast PC256 which is manufactured by Don Construction Product (DCP). It is a super-plasticizing admixture based on Poly carboxylic, which complies with ASTM C494 types F and G. The recommended dosage by the manufacturer is between 0.2 to 1.2 L per 100 kg of cementitious materials.

Table 10 Technical properties of PC256 at 25 C.

Color	Yellowish to brownish liquid
Specific gravity	1.05 +- 0.02
Freezing point	-1 C
Chloride content EN934-2	Chloride-free
Dosage	0.2 – 1.2 (L/100kg of cement)

3.2 Mix Design.

3.2.1 Basalt Fiber Reinforced Seawater Sea Sand Concrete (BFR-SSSC) mix design.

Table 11 BFR-SSSC mix design.

OPC	S/C Ratio	(3/4)A/C	(3/8)A/C	W/C Ratio	BF content
1.0	1.75	1.45	1.3625	0.5	From 0% to 1.5%

OPC = Ordinary Portland Cement; S = Sand; C = Cement; W = Water; BF= Basalt Fiber; A=Aggregate.

Table 12 BFR-SSSC kg/m3 mix design.

OPC	¾ C. Aggregate	3/8 C. Aggregate	Sand	Water	BF
[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
400	580	545	700	200	5.4 to 36

3.2.2 Basalt Fiber Reinforced Seawater Sea Sand Mortar BFR-SSSM mix design.

Table 13 BFR-SSSM mix design.

OPC	S/C Ratio	W/C Ratio	BF content
1.00	2.5	0.485	From 0% to 2.0%

OPC = Ordinary Portland Cement; S = Sand; C = Cement; W = Water; BF= Basalt Fiber.

Table 14 BFR-SSSM kg/m3 mix design.

OPC	Sand	Water	BF
[kg]	[kg]	[kg]	[kg]
560	1400	280	5.4 to 47.5

3.3 Specimens Preparation.

3.3.1 BFR-SSSC and BFR-SSSM Mixing Procedure

For BFR-SSSC After Measuring the weight of each material in the mix, 25% of the water quantity to be used in the mix is mixed with the superplasticising agent. After that, the coarse and fine aggregate are dry mixed for 90 seconds, after that the sand is added and dry mixed with the aggregate with another 90 seconds, then 75% of the water which doesn't contain the superplasticizer is added to the mix followed by the cement and mixed until all the cement become wet and mixed well with the other ingredients followed by the rest of the water that contains the superplasticizer. Finally, the basalt fibers are added gradually with small portions to ensure good mixing and avoid fiber clogging. After the paste rests for 30 to 60 seconds and then is poured into pre-oiled molds and the molds are put on the vibrating plate. Same procedure is done to BFR-SSSM minus the coarse aggregate parts. The required time for the mixing procedure to be done is about 5 to 6 minutes from start to pouring.

3.3.2 BFR-SSSM Specimens.

Specimens are prepared for multiple tests of BFR-SSSM including two flexural strength tests, compressive strength, drying shrinkage, and setting time. For flexural and compressive strength tests, three specimens are prepared from every mix for every testing age (7,14,28) day. Therefore, for each flexural strength test, forty-five mortar beams of a size of (40x40x160) mm are made. In addition, forty-five cubes of a size of (50x50x50) mm are also used to assess the compressive strength of mortar. Ten (25x25x285) mm mortar prisms are cast to evaluate their drying shrinkage, and five specimens are made for setting time testing of mortar. In total 150 different specimens are made to evaluate BFR-SSSM.

Table 15 BFR-SSSM prepared specimens.

Test type	Specimen type	Mixes	Ages	Number of specimens	Total specimens
Three-point loading flexural strength	Beam	5	3	3	45
Four-point loading flexural strength	Beam	5	3	3	45
Compressive strength	Cube	5	3	3	45
Drying shrinkage	Prism	5	1	2	10
Setting time	-	5	1	1	5
Total					150

The calculation of the volume of all specimens and the volume of specimens of each mix are shown in **Table 16**. Where dry volume is 1.33 the size of wet volume of mortar. The total quantity of materials used for the whole flexural strength test of mortar and each mix

of specimens are mentioned in the tables below respectively. The same procedure is applied to the other tests of BFR-SSSM.

Table 16 Total quantity of materials needed for the flexural strength test for mortar.

Unit	Spc. size	9 Spc. mix (wet)	9 Spc. mix (dry)	Total volume 45 spc. (wet)	Total volume 45 spc. (dry)
[cum]	0.000256	0.002304	0.003064	0.011520	0.015322
[cc]	256.0	2304.0	3064.3	11520.0	15321.6

Spc. = Specimen.

Table 17 The total approximate quantity of materials needed for the testing of mortar.

Cement	Sea Sand	Seawater	Superplasticizer	Basalt Fiber
[kg]	[kg]	[kg]	[g]	[g]
13	33	7	243	605

Table 18 BFR-SSSM mix quantities.

Mix ID	BF	PC256 SP	BF	Admixture	OPC	S	Seawater
	[%]	[%]	[g]	[g]	[g]	[g]	[g]
BSM00	0.0	0.5	0.00	10.41	1100.0	2750.0	533.5
BSM05	0.5	0.5	23.14	10.41	1100.0	2750.0	533.5
BSM10	1.0	0.5	46.28	10.41	1100.0	2750.0	533.5
BSM15	1.5	0.5	69.42	10.41	1100.0	2750.0	533.5
BSM20	2.0	0.5	92.56	10.41	1100.0	2750.0	533.5

BF = Basalt Fiber; OPC = Ordinary Portland Cement; S = Sea Sand; A = Aggregate; SP= Superplasticizer.

Flexural strength beams are cast in (40x40x140) mm steel molds, and compressive strength cubes are cast in (50x50x50) mm steel molds. The specimens are put on a vibrating table and then left in their molds for 24 hours covered with plastic sheets, and then are demolded from the casing and cured by submerging in tap water until the testing time, and the same procedure is done for the compressive strength test cubes of mortar.



Figure 24 Molded mortar specimens for flexural strength test.

For drying shrinkage, mortar is poured in (25x25x285) mm steel molds that are specialized to be used for drying shrinkage testing where a place for measuring bolts is present. The specimens are put on a vibrating table and then left in their molds for 24 hours covered with plastic sheets, and then are demolded from the casing and cured by submerging in tap water until the testing time.



Figure 25 BFR-SSSM drying shrinkage specimen.

3.3.3 BFR-SSSC specimens.

Specimens are prepared for multiple tests of BFR-SSSC including compressive strength, flexural strength, split-tensile strength, RCPT, water absorption, in addition to workability.

For split tensile strength and compressive strength tests thirty-six (150x300) mm concrete cylinders are made for each, as three specimens are made for four mixes at three ages. For flexural strength of concrete twenty-four (75x75x285) mm concrete beams are made as three specimens are made for four mixes at two ages. In addition, two cylinder specimens are also made for each mix to test the RCPT and water absorption of BFR-SSSC. In total, 144 concrete cylinders were cast and demolished in this experiment. Furthermore, workability is also evaluated for each mix after mixing.

Table 19 BFR-SSSC prepared specimens.

Test type	Specimen type	Mixes	Ages	Number of specimens	Total specimens
Split tensile strength	Cylinder	4	3	3	36
Compressive strength	Cylinder	4	3	6	72
Flexural strength	Beam	4	2	3	24
RCPT durability	Cylinder	4	1	1	4
Water Absorption	Cylinder	4	1	1	4
Workability	Slump cone	4	1	1	4
					144

Since the size of the specimen is 150*300 mm cylinder for split tensile strength, compressive strength, and durability tests, the calculation of the volume of all specimens and the volume of specimens of each mix are shown in **Table 20**. Where dry volume is 1.54 the size of the wet volume of concrete. The total quantity of materials used for compressive strength and split tensile strength testing of concrete, and each mix of specimens are mentioned in **Table 21** and **Table 22** respectively. The same procedure is done for the other tests.

Table 20 The volume of concrete specimens for compressive and split tensile strength test of BFR-SSSC.

Unit	One Spc. volume	11 Spc. Mix (wet) volume	11 Spc. Mix (dry) volume	Total 84 Spc. (wet) volume	Total 84 Spc. (dry) volume
m3	0.00530	0.05832	0.08981	0.44528	0.68574

Spc. = Specimen.

Table 21 The total approximate quantity of materials used for compressive and split tensile strength BFR-SSSC tests.

OPC	Sea Sand	3/4 Ca	3/8 Ca	Seawater	Superplasticizer	Basalt Fiber
[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
275	480	398	374	137	5.5	13

OPC = Ordinary Portland; Ag = Coarse aggregate.

Table 22 BFR-SSSC mix quantities (11 specimens each).

Mix ID	BF	SP	BF	Ad	OPC	S-Sand	(3/8)A	(3/4)A	Seawater
	[%]	[%]	[g]	[g]	[kg]	[kg]	[kg]	[kg]	[kg]
BSC00	0	0.5	0	0	35.92	62.87	48.95	52.09	17.96
BSC05	0.5	0.5	1077.71	193.98	35.92	62.87	48.95	52.09	17.96
BSC10	1.0	0.5	2155.41	193.98	35.92	62.87	48.95	52.09	17.96
BSC15	1.5	0.5	3233.12	310.37	35.92	62.87	48.95	52.09	17.96

BF = Basalt Fiber; OPC = Ordinary Portland Cement; S-Sand = Sea Sand; A = Aggregate. SP=

Superplasticizer.

For compressive and tensile strength testing of BFR-SSSC, the mix is poured in 150x300 mm cylindrical molds made of steel, after pouring the molds are put on a vibrating table. Then, the specimens are left in their molds for 24 hours covered with plastic sheets and then are demolded from the casing and cured by submerging them in tap water until the testing time, the same procedure is done for all specimens. The same procedure is done for the specimens used for water absorption and RCPT testing. For Flexural strength, the mix is poured in (75x75x280) mm steel molds, after pouring the molds are put on a vibrating table. Then, the specimens are left in their molds for 24 hours covered with plastic sheets and then are demolded from the casing and cured by submerging them in tap water until the testing time, the same procedure is done for all specimens.



Figure 26 Casted concrete in the molds (left). Submerged concrete specimens in tap water (right).



Figure 27 BFR-SSSC flexure strength specimens.

3.4 Test Procedure

3.4.1 Fresh Properties

3.4.1.1 Workability and Slump

To assess the workability of freshly mixed concrete a slump test is done for each mix as per ASTM C143 which is a standard testing method for the consistency and workability of freshly mixed concrete. A sample of the mixed concrete is placed into the slump cone in three layers where each layer is tamped 25 times then the cone is lifted upward, and the

difference in height between the concrete and the cone is reported as the slump value, the larger the slump value is the more the concrete is workable.

3.4.1.2 Initial and Final Setting Times

Initial and final setting times are tested for SSSM as per ASTM C191 where 500 grams of cement are used for each mix with the other proportions of materials listed previously. Where after mixing the paste, it rests for 30 minutes, and then it is put in the molds using and set under the needle of an automatic Vicat apparatus shown in **Figure 28**. Finally, the readings for initial and final setting time are taken for each mix individually.



Figure 28 Automatic Vicat apparatus device used to measure initial and final setting time.

3.4.2 Hardened Properties

3.4.2.1 Compressive Strength and Elastic Modulus Testing.

For BFR-SSSC the testing is done according to ASTM C39 where concrete is first mixed and prepared as cylinder specimens. After specimen preparation, curing is done where the specimens are cured while submerged under tap water, when the due time is reached, concrete specimens are taken out of the water, surface dried, and capped (if needed) which ensures even loading from the testing machine. Then, strain gauges are glued to the surface of the concrete specimen, where each specimen has two strain gauges, one in the axial direction, and the other in the perpendicular direction to the applied force direction. After that, the concrete cylinder is positioned between the plates of the compressive strength testing machine, and the strain gauges are connected to the data logger. Furthermore, two LVDTs are also attached to the specimen and connected to the data logger. Then a gradual, axial, and uniformly distributed compressive loading is applied at a steady rate until a failure occurs in the concrete specimen. After recording the data of each specimen including axial and lateral strains, loading rate, deflection readings of the two LVDTs. The specimen's maximum supported load is divided by its cross-sectional area which gives its compressive strength, and the data collected of the strain gauges gives the stress-strain curve which also gives the modulus of elasticity of the specimen. In addition, the data from the LVDTs give another way of measuring the modulus of the elasticity of the sample. The loading rate applied is 1 kN per second.



Figure 29 Strain gauges attaching to the cylindrical concrete samples (left). Capping of the samples (right).



Figure 30 BFR-SSSC cylindrical sample under compression testing.

For BFR-SSSM, compressive strength testing is carried out as per ASTM C109. The test involves preparing mortar specimens where the mixed mortar is placed into their molds. After curing the specimens are surface dried and put in a closed-loop hydraulic testing machine where a compressive load is applied to the specimen at a controlled constant rate of 1.2 kN/sec. The date for each set is taken as an average of 3 specimens. The compressive strength is equal to the value of the greatest load sustained by the mortar specimen divided by the cross sectional area of the specimen.

3.4.2.2 Flexural Strength and Toughness Testing

The test is done for BFR-SSSC using simple beam with four-point loading as per ASTM C78, casting three (75x75x280) mm prism concrete specimens for each mix at two different ages. After specimen preparation, curing is done where the specimens are cured while submerged under tap water. When the due time is reached, concrete specimens are taken out of the water, surface dried, and placed in the closed-loop hydraulic testing machine with a load cell of 250kN capacity where a four-point loading is carried out on the specimen. Furthermore, the deflection rate at the middle of the specimen is measured along with the loading rate using LVDT attached to a data logging machine. The loading rate applied is 0.1 kN/sec.



Figure 31 BFR-SSSC beam surface-dried specimens (a). BFR-SSSC beam specimen under loading (b).

Testing of the BFR-SSSM mortar's flexural strength is done according to two ways of measurement; The first one is the Three-point loading done according to ASTM C348. In this test, the specimens are prepared according to the same standard that is mentioned earlier in this research. After curing the specimens, and when the testing time comes, specimens are removed from the water and surface dried and put in the testing machine,

which is a closed-loop hydraulic testing machine where three-point loading is carried out on the specimen. A load cell of 250 kN capacity is used to monitor the load-bearing resistance of specimens. Where two displacement transducers are attached to the mid-section of the specimens on both sides. The rate of loading is load-controlled loading of 0.1 kN/sec. The data for each set is taken as an average of 3 specimens. This test method is also used for the determination of first-peak load (P) and residual loads corresponding to the deflection of L/600 and L/150. The modulus of rupture is to be calculated as **Eq 3.1**.

$$f = \frac{P L}{b d^2} \quad (3.1)$$

Where b: specimen width, d: depth, L: Length, P: Peak load.

The second test is the four-point loading done according to ASTM C78 where the samples are treated as the previous testing method except for the setup of the loading mechanism. For this test the loading rate is set to be 0.1 kN/sec and carried with a 250kN capacity loading cell. Furthermore, an LVDT is set at the center of the specimen to measure the deflection rate along the loading rate, where the LVDT is connected to data logging machine. The difference between the two ways of measuring is that the Three-point loading method forces the beam to fail directly under the center of the loading, while the four-point loading method the middle one-third of the beam is stressed uniformly so the beam fails at the weakest point at this distance rather than only at exactly one point which makes it a more conservative method of measuring.

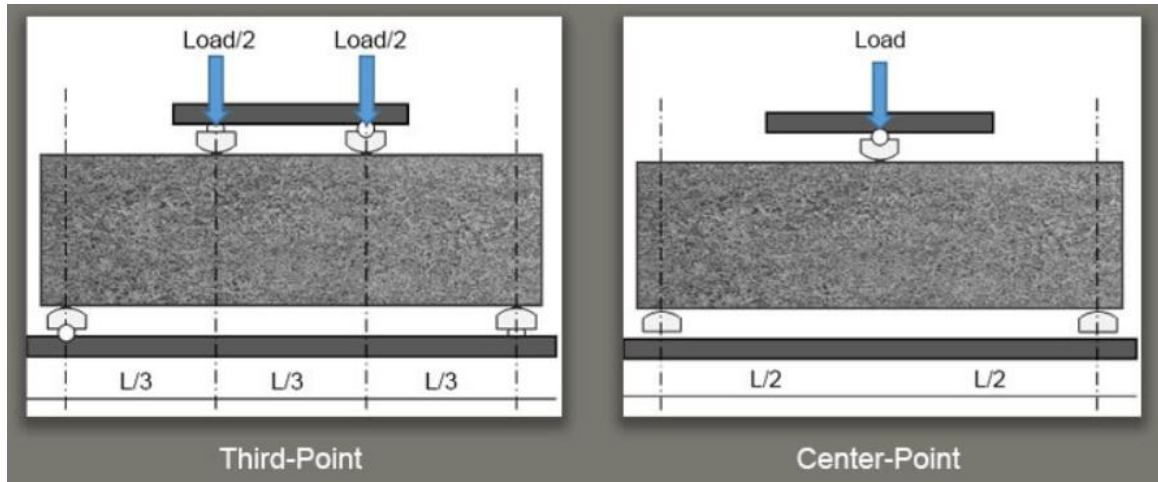


Figure 32 Loading mechanisms of four-point and Three-point loading testing.



Figure 33 BFR-SSSM specimen placed in a three-point loading machine according to ASTM C348.



Figure 34 BFR-SSSM specimen placed in a four-point loading machine according to ASTM C78.

3.4.2.3 Concrete Split Tensile Strength Test.

The test is done according to ASTM C496 which is the standard method to test splitting tensile strength of concrete. Freshly mixed concrete is first mixed and poured into cylinder specimens, these steps are shown and explained previously in this research. After specimen preparation, curing is done where the specimens are cured while submerged under tap water. When the due time is reached, concrete specimens are taken out of the water, surface dried, and placed between the machine's bearing plates. After that, the concrete specimen is subjected to diametral compressive exerted along its length. The load causes tensile stresses in the sectional plane and then a tensile failure occurs because the areas of load application are in a state of triaxial compression which allows them to withstand very high compressive stresses. Thin plywood bearing strips (3.0mm) are placed between the plates and the concrete to distribute more evenly. Finally, to calculate splitting tensile strength, the greatest value of load sustained by the concrete cylinder is divided by a geometrical factor to get the splitting tensile strength, in this case, the calculations are done by the machine directly. The load rating applied is 1.0MPa/min.

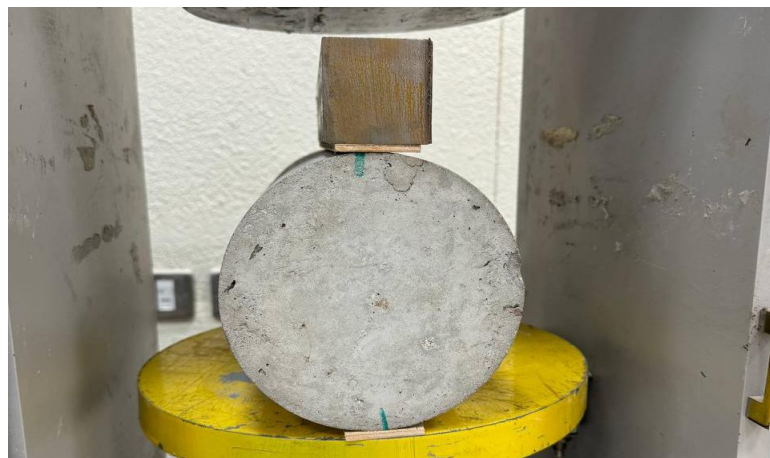


Figure 35 BFR-SSSC specimen split tensile strength testing.

3.4.2.4 Concrete Water Absorption.

This test is done as per BS 1881 Part 122, where after curing the specimens, each specimen is cut as discs with 100 mm in diameter and 60 mm in height. Then, each disc is marked and placed in the oven for 72 hours at a temperature of 110 C. then cooled for 24 hours in an airtight vessel. After that each disc is weighed as M1, then immersed in water tank for 30 minutes then weighed again as M2. The absorption then is calculated as **Eq 3.2**.

$$Absorption = \frac{M2-M1}{M1} \times 100 \quad (3.2)$$



Figure 36 Water absorption BFR-SSSC specimens' discs preparation.



Figure 37 BFR-SSSC water absorption specimens placed in oven for 72 hours.

3.4.2.5 Mortar Drying Shrinkage Test.

This test is done according to ASTM C157 where two specimens are prepared for each mix of mortar, demolded, and cured. The measurements of the length changing are taken using specialized equipment at 1,7,14,28,35,42,49,70,90 days. And the shrinkage is calculated using **Eq. 3.3**.

$$L = (Lx - Li) \times \frac{100}{G} \quad (3.3)$$

Where L is the length change (%), Lx is the comparator reading of specimen at age x, Li is the initial comparator reading of specimen, and G = 250 for prisms with 285mm length.



Figure 38 Measurement of drying shrinkage of BFR-SSSM.

3.4.3 Microstructure and Phase Identification

3.4.3.1 SEM-EDS

SEM and EDS terms refer to Scanning electron microscopy and energy-dispersive X-ray spectroscopy. SEM is an advanced surface-analyzing tool used to analyze different material surfaces and identify their contaminants. SEM generates electrons by passing current through a metallic filament which is considered as cathode, these electrons are then accelerated toward the anode using high voltage where they are subjected to a series of processes resulting in the collimating of the electrons forming a beam of electrons aimed at the sample surface. When these electron beams hit the surface of the sample, secondary electrons, and backscattered electrons are generated. The secondary electrons are collected by detectors and utilized to fluoresce a scintillating material. The backscattered electrons are electrons that bounce inside the sample and exit it with much lower energy. These electrons are important to identify the atomic number of different areas in the specimen.

Using quantum mechanics rules, EDS analysis takes advantage of the physical phenomena that occur when the electron beams hit the sample to generate a spectrum used to identify different elements in the specimen. Also, it generates overlay mapping presenting the high element concentrations in the SEM images [101], [102].

BFR-SSSC samples are analyzed using SEM-EDS. Where samples of each group are broken into tiny pieces, (20mm in diameter approx.) and then polished. After that, they are dried using methanol solvent and then dried using blown compressed gas. Finally, they are coated with a thin conductive layer of gold and placed in the SEM-EDS instrument. The SEM-EDS instrument used is JEOL JSM-6610LV which uses a backscattered electron

detector, low vacuum secondary electron detector, and energy dispersive X-ray analyzer. In addition to wavelength dispersive X-ray analyzer. Images taken of each sample started from 1 μ m (x10'000 magnification) up to 100 μ m (x250 magnification). **Figure 39** shows the placement and analysis of the specimens.



Figure 39 Placement of specimens plated with gold sheets in SEM-EDS instrument (left). SEM-EDS instrument (right).

3.4.3.2 X-Ray Diffraction Analysis (XRD)

X-ray diffraction (XRD) is an analytical method that analyzes solid or liquid samples to quantify mineral compositions and obtain different characteristics including phase compositions, crystal structures, and powder orientations. After placing the sample in the holder inside the XRD instrument, the instrument produces X-rays which illuminate the targeted sample. The sample diffracts these rays into the detector. The angle at which the sample or the detector is placed is then changed gradually, this angle is called diffraction angle (2θ) which can be identified as the angle between the diffracted beam and the incident. The intensity of the diffracted X-ray beams along with the angle at which the X-rays are diffracted are recorded [103]. In this analysis, both SSSM and SSSC samples have

been prepared by grinding the samples into a powder $< 3\ \mu\text{m}$ which passes through a $250\ \mu\text{m}$ sieve. They are placed in the XRD instrument then and analyzed. The XRD instrument used in this analysis is Rigaku Ultima IV. **Figure 40** shows the placement and analysis of the specimens.



Figure 40 XRD instrument (left). SSSC and SSSM sample placement inside XRD analysis instrument (right).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Fresh Properties

4.1.1 BFR-SSSC Workability.

Studying the workability of the BFR-SSSC mixes is done with each patch of the mixes.

The results of the slump test are shown in **Table 23**.

Table 23 SSSC workability with basalt fiber and superplasticizer.

Mix ID	BF	SP	Slump
	[%]	[%]	[cm]
BSC00	0.0	0	14
BSC05	0.5	0.5	17
BSC10	1.0	0.5	11
BSC15	1.5	0.8	9

BF = Basalt Fiber; SPR = Superplasticizer.

Results show that basalt fiber content highly affects the workability of SSSC, where the super-plasticizing agent must be used in the concrete mix. However, when increasing the basalt fiber content up to 1.5%, the superplasticizer reaches its maximum dosage, and any additional quantity causes significant retardation to the mix setting time. Therefore, there is no point in increasing the basalt fiber content above 1.5% for concrete, and above 2.0% for mortar. BF content significantly reduced the workability of the mortar and concrete due to the reason that it is a high water-absorbing material. When increasing the dosage of the superplasticizer in the SSSM beyond 1.0% of volume, retardation of mortar is significantly increased.

4.1.2 Initial setting time

The initial setting time of BFR-SSSM is compared for all the mixes where it is shown in **Figure 41**.

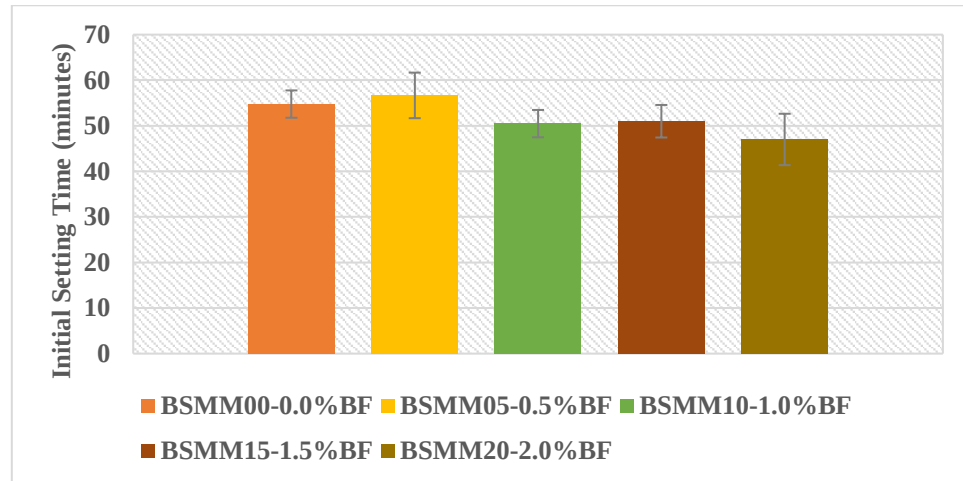


Figure 41 Initial setting time of BFR-SSSM.

4.1.3 Final Setting time

The final setting time of BFR-SSSM is compared for all the mixes where it is shown in **Figure 42**.

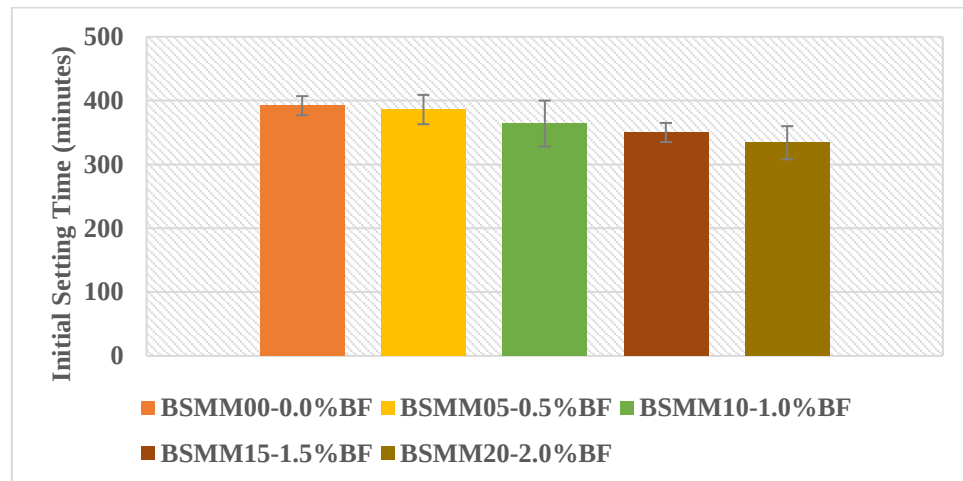


Figure 42 Final setting time of BFR-SSSM.

Observing the initial and final setting time shows that basalt fiber content does not significantly affect the intimal setting time nor the final setting time of SSSM.

4.2 Hardened Properties

4.2.1 Compressive Strength and Elastic Modulus

4.2.1.1 BFR-SSSM Compressive Strength.

The compressive strength values of BRF-SSSM are listed in **Table 24**. In addition, **Figure 43** shows the compressive strength of BRF-SSSM at different ages.

Table 24 BFR-SSSM compressive strength test average results.

Mix ID	SP	7 days	14 days	28 days
	[%]	MPa	MPa	MPa
BSM00	0.5	14.21	19.76	22.24
BSM05	0.5	14.72	20.37	22.77
BSM10	0.5	16.30	23.25	26.05
BSM15	1.0	16.80	23.18	25.73
BSM20	1.0	15.42	21.49	24.27

BF = Basalt Fiber; SP = Superplasticizer.

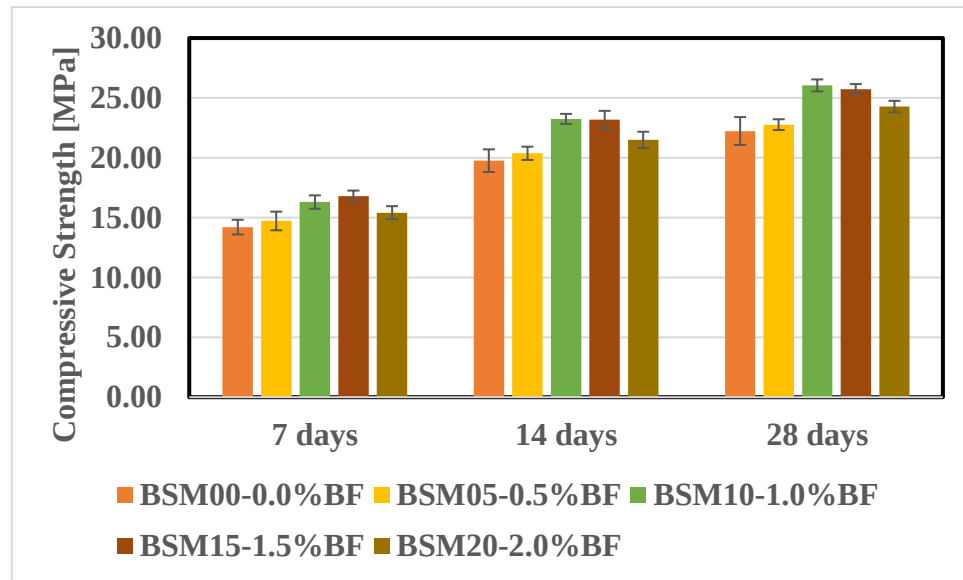


Figure 43 BFR-SSSM compressive strength for each group at different ages.

The increase and decrease of compressive strength of the SSSM specimens reinforced with BF comparing to the compressive strength of SSSM with 0.0% BF content are listed in **Table 25**. In addition Fisher's LSD method is used for mixes grouping.

Table 25 Fisher LSD method grouping (95% Confidence) and mean for BFR-SSSM compressive strength at 28 days.

Mix ID	N	Mean	Grouping				Increase/Decrease
BSM00	3	22.24	A				-
BSM05	3	22.77		B			2.4%
BSM10	3	26.05			C		17.1%
BSM15	3	25.73			C		15.7%
BSM20	3	24.27				D	9.2%

Means having different letters have a significant difference. Pooled St. Deviation = 0.256.

Results show that the additional basalt fibers slightly increase the compressive strength of SSSM, peaking at 1.0% basalt fiber content, which is different from what is observed in SSSC.

4.2.1.2 BFR-SSSC Compressive Strength.

The compressive strength values are taken as an average of 6 specimens for each mix of BFR-SSSC. Where the average results for each mix at each age are shown in **Table 26**.

Table 26 BFR-SSSC compressive strength test average results.

Mix ID	SP	7 days	14 days	28 days
	[%]	MPa	MPa	MPa
BSCC00	0.5	20.4	28.0	31.1
BSCC05	0.5	18.7	26.8	30.1
BSCC10	0.5	18.5	26.1	28.8
BSCC15	0.5	18.0	25.1	27.7

BF= Basalt Fiber; SP= Superplasticizer.

Figure 44 also shows the compressive strength for the different mixes at different ages.

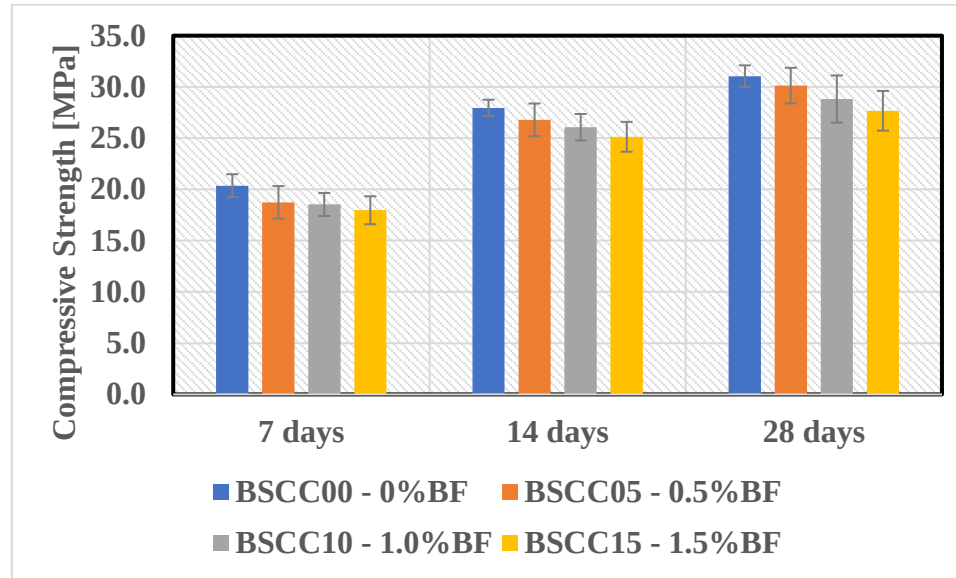


Figure 44 BFR-SSSC compressive strength for each group at different ages.

The increase and decrease of compressive strength of the SSSC specimens reinforced with BF comparing to the compressive strength of SSSC with 0.0% BF content are listed in **Table 27**. In addition Fisher's LSD method is used for mixes grouping.

Table 27 Fisher LSD method grouping (95% Confidence), standard deviation, and mean for BFR-SSSC compressive strength at 28 days.

Mix ID	N	Mean	Grouping			S. Deviation	Increase/Decrease
BSCC00	6	31.1	A			1.54	-
BSCC05	6	30.1	A	B		1.46	-3%
BSCC10	6	28.8		B	C	1.87	-7%
BSCC15	6	27.7			C	0.89	-11%

Means having different letters have a significant difference. Pooled St. Deviation = 1.48

Results show that the additional basalt fiber reduces the compressive strength of SSSC by a small margin, whereas at 1.5% BF content, the compressive strength of SSSC is reduced by 11% compared to control specimens.

Regarding the stress-strain curves, the average stress-strain curves for each mix are shown in **Figure 45** where in the same figure the stress strain curves are also shown for 40% of the ultimate compressive strength.

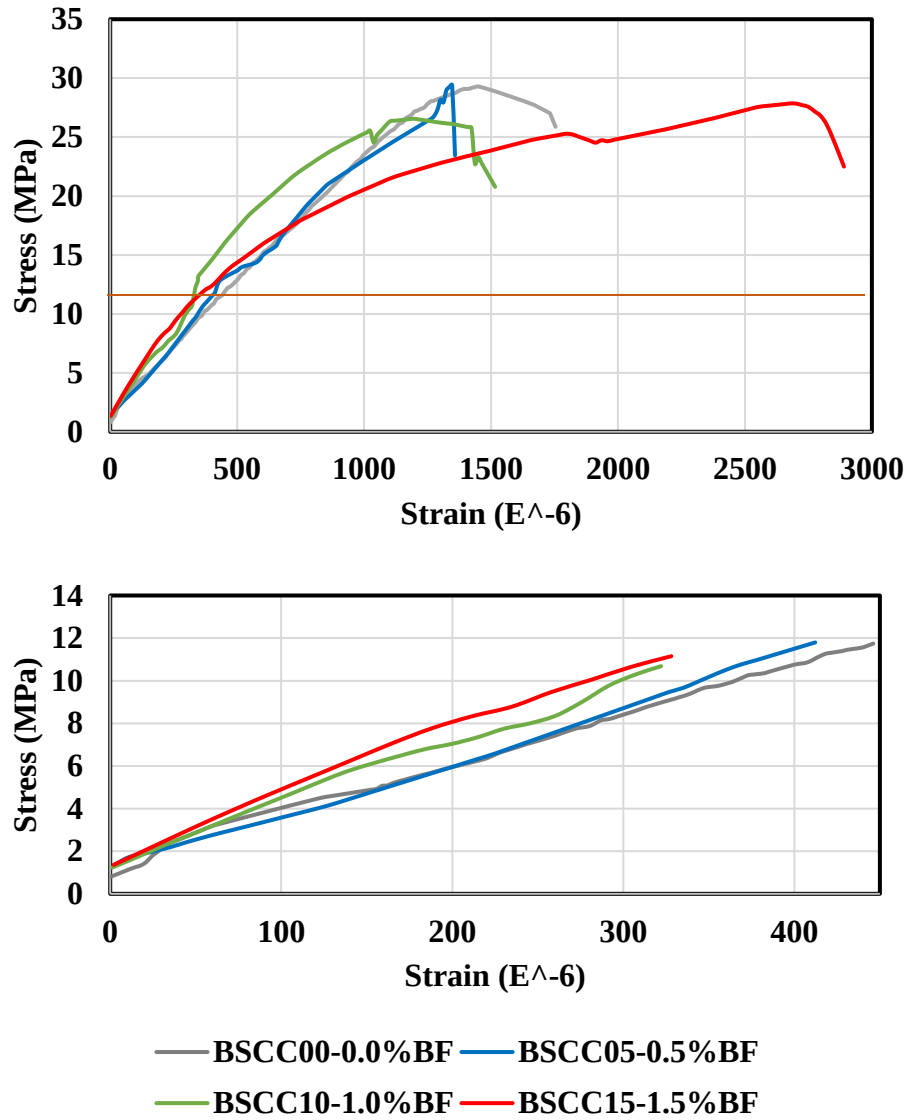


Figure 45 Average stress-strain curves for each mix of BFR-SSSC at 28 days.

From the stress-strain curves obtained for the BFR-SSSC different mixes, the average elastic Young's modulus E at 28-day age is calculated from compressive strength test for

each mix, presented and compared in **Table 28**. Where they are calculated at 40% of the ultimate compressive strength.

Table 28 BFR-SSSC modulus of elasticity at 28 days.

Mix ID	BF Content	Modulus of Elasticity	Increase/Decrease
	[%]	[GPa]	
BSCC00	0.0	26.32	-
BSCC05	0.5	28.62	+8.7%
BSCC10	1.0	33.17	+26.0%
BSCC15	1.5	33.99	+29.2%

Table 29 Average density of BFR-SSSC at 90 days.

Mix ID	Average Density	Increase / Decrease
	[kg/m ³]	
BSCC00	2210.62	-
BSCC05	2186.62	-1.1%
BSCC10	2063.27	-6.7%
BSCC15	2059.02	-6.9%

Results show that higher basalt fibers content enhances the modulus of elasticity of SSSC where an increase of 29% is observed at 1.5% BF content.

Based on the results shown in the previous section, basalt fibers reduced the compressive strength of SSSC up to 11% at 1.5% of BF content. However, the reduction of compressive strength in SSSC is not significant and could be tolerated when tensile strength is needed. At the same time, increasing BF content showed enhancement in the modulus of elasticity of SSSC. In addition, BF content does not noticeably affect the compressive strength of SSSM where a slight increase in the compressive strength is noticed when additional BF content is added, peaking at 1.0% BF content by an increase of 17.1%. The results of such an increase could be because BF acts as bridging for microcracks. Regarding the density of the concrete, **Table 29** shows a slight reduction in density when increasing BF content in SSSC.

4.2.2 Flexural Strength and Split Tensile Strength

4.2.2.1 BRF-SSSM Flexural Strength (Three-Point Loading).

Flexural strength of BFR-SSSM is calculated in two different ways, the first one is three-point loading method which forces the specimen to fail at the middle of the span. The averages of the results obtained are listed in **Table 30** and are visualized in **Figure 46**.

Table 30 BFR-SSSM flexural strength (three-point loading) test average results.

Mix ID	SP	7 days	14 days	28 days
	[%]	MPa	MPa	MPa
BSM00	0.5	2.11	2.85	3.40
BSM05	0.5	2.44	3.14	3.83
BSM10	0.5	2.87	3.74	4.51
BSM15	1.0	3.01	4.00	4.84
BSM20	1.0	2.92	3.94	4.59

BF= Basalt Fiber; SP= Superplasticizer.

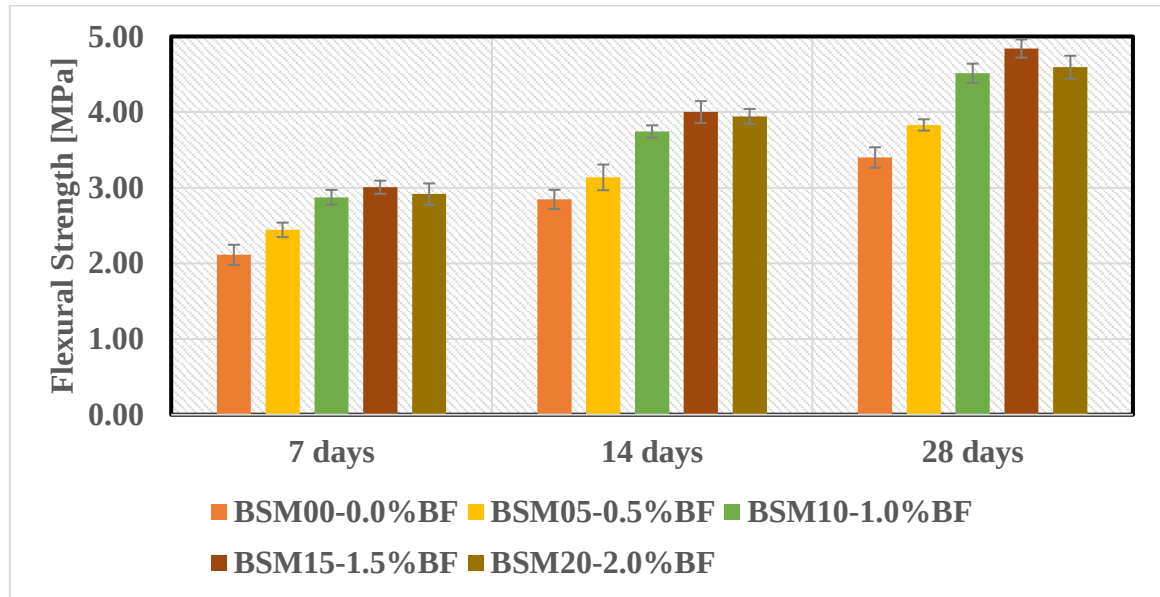


Figure 46 BFR-SSSM Flexural strength (three-point loading) for different mixes content at different ages.

The increase and decrease of flexural strength (Three-Point Loading) of the SSSM specimens reinforced with BF comparing to the flexural strength of SSSM with 0.0% BF content are listed in **Table 31**. In addition Fisher's LSD method is used for mixes grouping.

Table 31 Fisher LSD method grouping (95% Confidence), standard deviation, and mean for BFR-SSSM flexural strength at 28 days under three-point loading.

Mix ID	N	Mean	Grouping				Increase/Decrease
BSM00	3	3.4000	A				-
BSM05	3	3.8300		B			+12.6%
BSM10	3	4.5133			C		+32.7%
BSM15	3	4.8400				D	+42.4%
BSM20	3	4.5900			C		+35.1%

Means having different letters have a significant difference. Pooled St. Deviation = 0.120.

According to the results obtained, basalt fibers significantly increase the flexural strength of SSSM, peaking at 1.5% basalt fiber content with a 42.4% increase in flexural strength compared to the control group. Furthermore, the specimens with higher basalt fiber content were shown to be more ductile than the ones with less basalt fiber content. **Figure 47** below show two different specimens with different basalt fiber content after testing them.

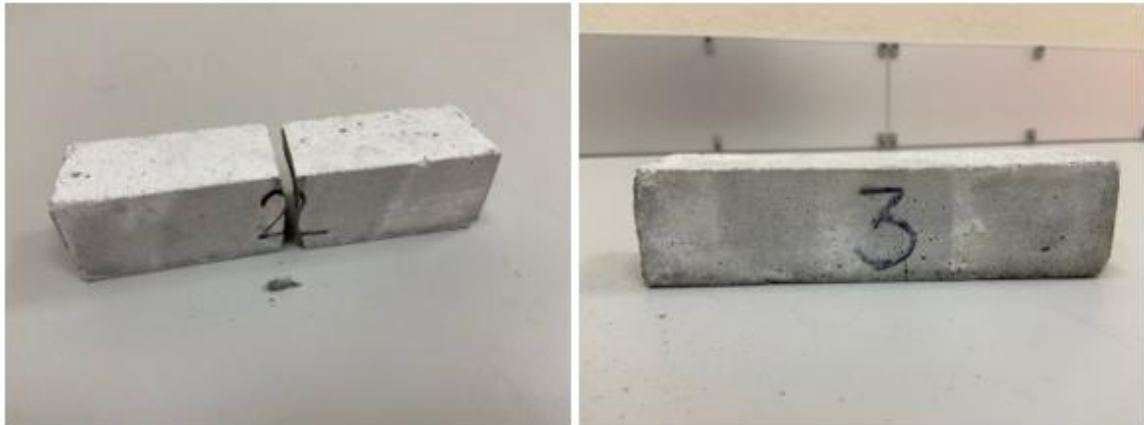


Figure 47 0.5% BF content SSSM specimen (left). 1.0% BF content SSSM specimen (right).

As shown in the **Figure 46**, the failure type changes based on the content of basalt fiber in the SSSM, where a noticeable difference in failure type is noticed during the testing of the mortar specimen. The additional quantity of basalt fiber present in the mortar caused the failure type to change from brittle to ductile, which is due to the additional tensile strength that the mortar gained with the additional basalt fiber content.

4.2.2.2 BRF-SSSM Flexural Strength (Four-Point Loading).

The second way in which flexural strength is calculated for BFR-SSSM is the (Four-Point Loading) method which is a more accurate way of calculating the flexural strength. The averages of the results obtained are listed in **Table 32** and are visualized in **Figure 48**.

Table 32 BFR-SSSM flexural strength (four-point loading) test average results.

Mix ID	SP	7 days	14 days	28 days
	[%]	MPa	MPa	MPa
BSMM00	0.5	2.42	3.10	3.36
BSMM05	0.5	3.04	3.89	4.15
BSMM10	0.5	3.16	4.02	4.42
BSMM15	0.5	3.28	4.15	4.65
BSMM20	0.5	3.46	4.10	4.55

BF= Basalt Fiber; SP= Superplasticizer.

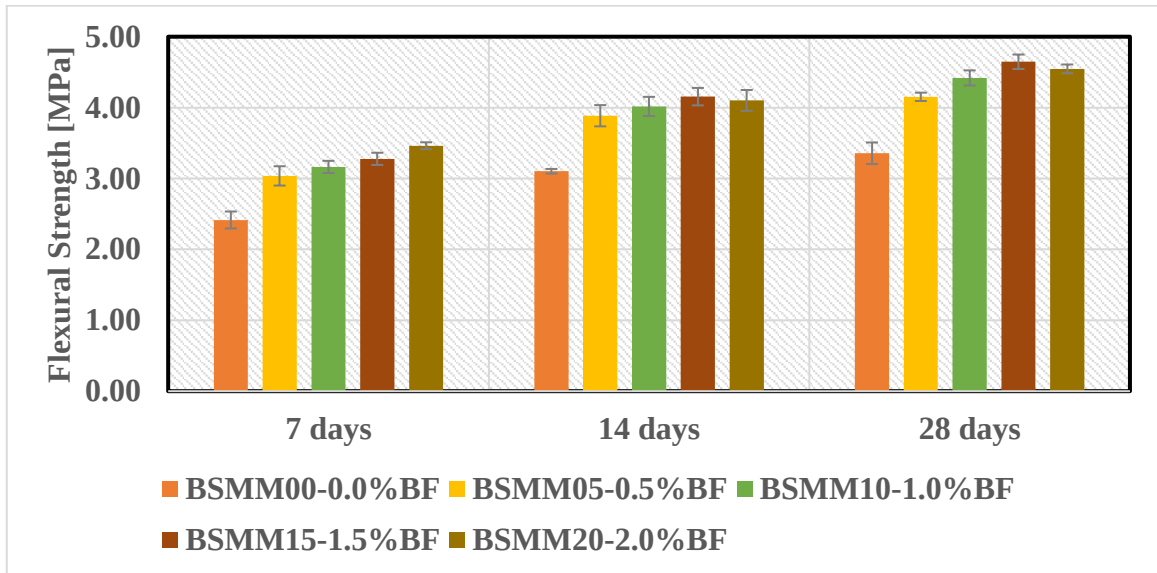


Figure 48 BFR-SSSM flexural strength under four-point loading versus BF content at different ages.

The increase and decrease of flexural strength (Four-Point Loading) of the SSSM specimens reinforced with BF comparing to the flexural strength of SSSM with 0.0% BF content are listed in **Table 33**. In addition Fisher's LSD method is used for mixes grouping.

Table 33 Fisher LSD method grouping (95% Confidence), standard deviation, and mean for BFR-SSSM flexural strength at 28 days under four-point loading.

Mix ID	N	Mean	Grouping				Increase/Decrease
BSMM00	3	3.36	A				-
BSMM05	3	4.15		B			+23.7%
BSMM10	3	4.42		B	C		+31.7%
BSMM15	3	4.65			C		+38.5%
BSMM20	3	4.55			C		+35.5%

Means having different letters have a significant difference. Pooled St. Deviation = 0.161.

Results obtained from the four-point loading testing of BFR-SSSM beams for flexural strength show that the addition of basalt fibers increase the flexural strength of BFR-SSSM by a significant margin where an addition of 38.5% increase in flexural strength at 28 days is observed when 1.0% of basalt fibers is added to the seawater sea sand mortar paste.

4.2.2.3 BFR-SSSC Split Tensile Strength.

Split tensile strength of BFR-SSSC average values for each mix are listed below in **Table 34** and visualized in **Figure 49**.

Table 34 BFR-SSSC split tensile strength test average results.

Mix ID	SP	7 days	14 days	28 days
	[%]	MPa	MPa	MPa
BSC00	0.0	1.6	2.0	2.7
BSC05	0.5	2.2	2.7	3.6
BSC10	0.5	2.8	3.3	4.4
BSC15	0.8	2.9	3.6	4.8

BF= Basalt Fiber; SP= Superplasticizer.

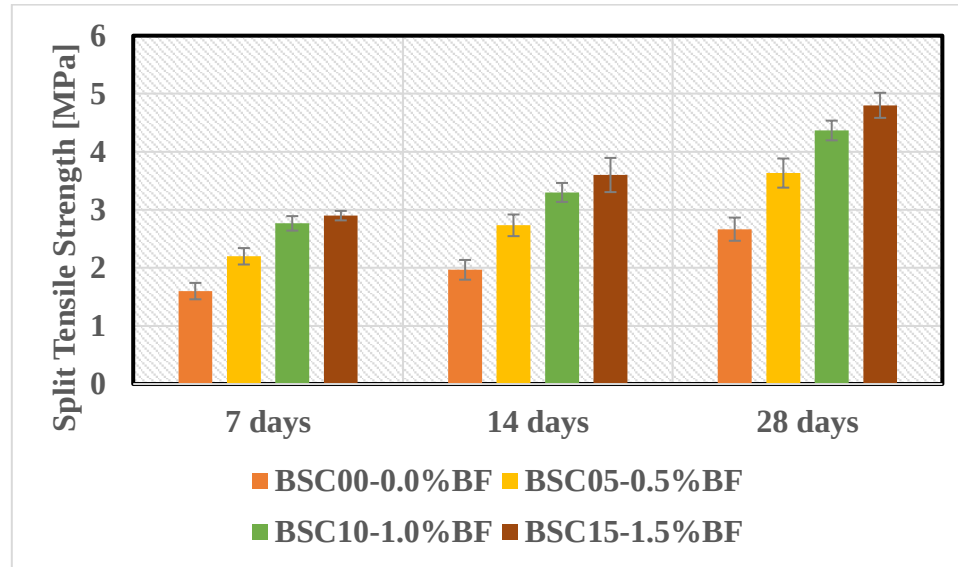


Figure 49 BFR-SSSC split tensile strength versus BF content at different ages.

The increase and decrease of split tensile strength of the SSSC specimens reinforced with BF comparing to the split tensile strength of SSSC with 0.0% BF content are listed in **Table 35**. In addition Fisher's LSD method is used for mixes grouping.

Table 35 Fisher LSD method grouping (95% Confidence), standard deviation, and mean for BFR-SSSC split tensile strength at 28 days.

Mix ID	N	Mean	Grouping			Increase/Decrease
BSC00	3	2.667	A			-
BSC05	3	3.633		B		+36.3%
BSC10	3	4.367			C	+63.8%
BSC15	3	4.800			C	+80.0%

Means having different letters have a significant difference. Pooled St. Deviation = 0.328.

Results show that the additional basalt fiber significantly increased the split tensile strength of SSSC, where at 1.5% basalt fiber content, the tensile strength of concrete increased by 80% when compared to the control specimens. In addition, observing the failure type of concrete, specimens with higher basalt fiber content were shown to be much more ductile compared to specimens with low amount of basalt fiber content.



Figure 50 Tested BFR-SSSC specimens with different BF content.

4.2.2.4 BFR-SSSC Flexural Strength.

The flexural strength of BFR-SSSC is calculated using (Four-Loading Point) method where the averages of the values obtained are listed in **Table 36** and visualized in **Figure51**.

Table 36 BFR-SSSC Flexural strength test average results.

Mix ID	SP	7 days	28 days
	[%]	MPa	MPa
BSCC00	0.5	1.9	2.4
BSCC05	0.5	2.2	3.2
BSCC10	0.5	2.5	3.5
BSCC15	0.5	3.0	4.1

BF= Basalt Fiber; SP= Superplasticizer.

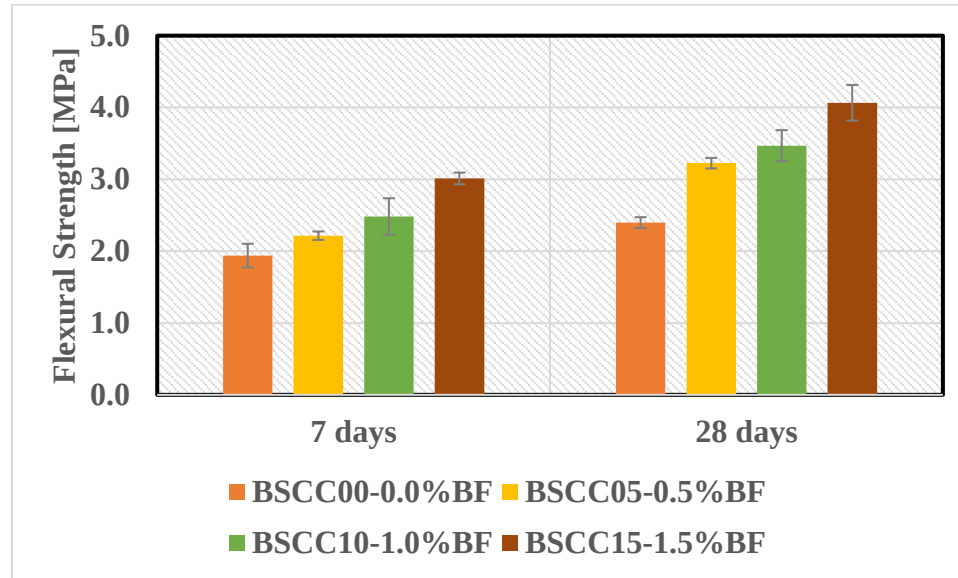


Figure 51 BFR-SSSC flexural strength versus BF content at different ages.

The increase and decrease flexural strength of the SSSC specimens reinforced with BF comparing to the flexural strength of SSSC with 0.0% BF content are listed in **Table 37**.

In addition Fisher's LSD method is used for mixes grouping.

Table 37 Fisher LSD method grouping (95% Confidence), standard deviation, and mean for BFR-SSSC flexural strength at 28 days.

Mix ID	N	Mean	Grouping			S. Deviation	Increase/Decrease
BSC00	3	2.398	A			0.092	-
BSC05	3	3.225		B		0.089	+34.5%
BSC10	3	3.468		B		0.265	+44.6%
BSC15	3	4.066			C	0.434	+69.5%

Means having different letters have a significant difference. Pooled St. Deviation = 0.262

Results show that the additional basalt fiber significantly increased the flexural strength of BFR-SSSC, where at 1.5% basalt fiber content, the flexural strength of concrete increased by 70% when compared to the control specimens. In addition, observing the failure type of concrete, specimens with higher basalt fiber content were shown to be much more ductile compared to specimens with low amount of basalt fiber content.

4.2.3.1 BRF-SSSC Deflection and Toughness

Measuring the deflection at the center of the 28-day specimens when the four-point loading is applied, where the deflection at the peak load and the maximum deflection before total failure are listed in **Table 38**.

Table 38 BFR-SSSC specimen average deflection under four-point loading at 28-day age.

Mix ID	BF	Peak load	Deflection at peak load	Increase/Decrease
	[%]	[kN]	mm	[%]
BSCC00	0.0	2.398	0.128	-
BSCC05	0.5	3.225	0.177	+38.3%
BSCC10	1.0	3.468	0.115	-10.2%
BSCC15	1.5	4.066	0.129	+0.8%

The average load-deflection curves of BFR-SSSC specimens are shown in **Figure 53** for each mix at 28-day age.

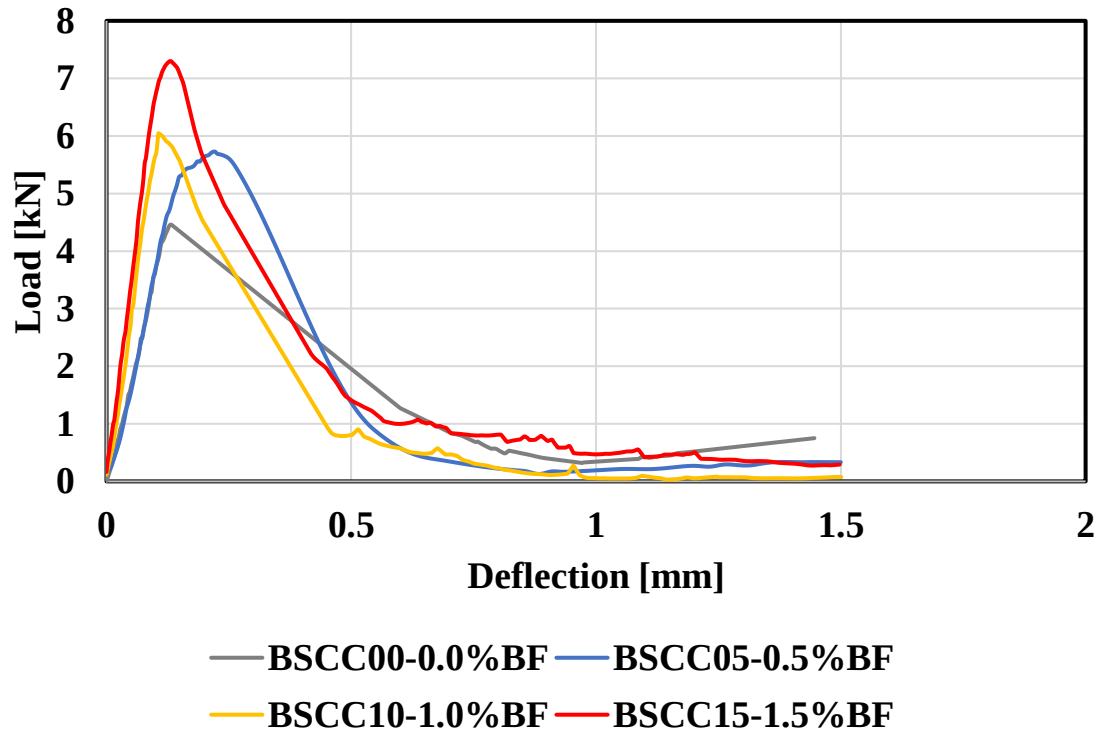


Figure 53 Lod-Deflection average curves for BFR-SSSC at 28 days.

In order to calculate toughness using load-deflection curves, it is essential to calculate values related to the first crack deflection. Here, the deflection indices to be studied are I5, I10 and I20. Therefore, values of deflection at δ , 3δ , 5.5δ , and 10.5δ are calculated for each mix and represented in **Table 39**.

Table 39 Values of δ to calculate toughness.

Mix ID	BF	δ	3δ	5.5δ	10.5δ
	[%]	[mm]	[mm]	[mm]	[mm]
BSCC00	0.0	0.111476	0.334428	0.613118	1.170498
BSCC05	0.5	0.122496	0.367488	0.673728	1.286208
BSCC10	1.0	0.088668	0.266004	0.487674	0.931014
BSCC15	1.5	0.077984	0.233952	0.428912	0.818832

The calculated toughness values of BFR-SSSC for each mix are shown in Figure 54.

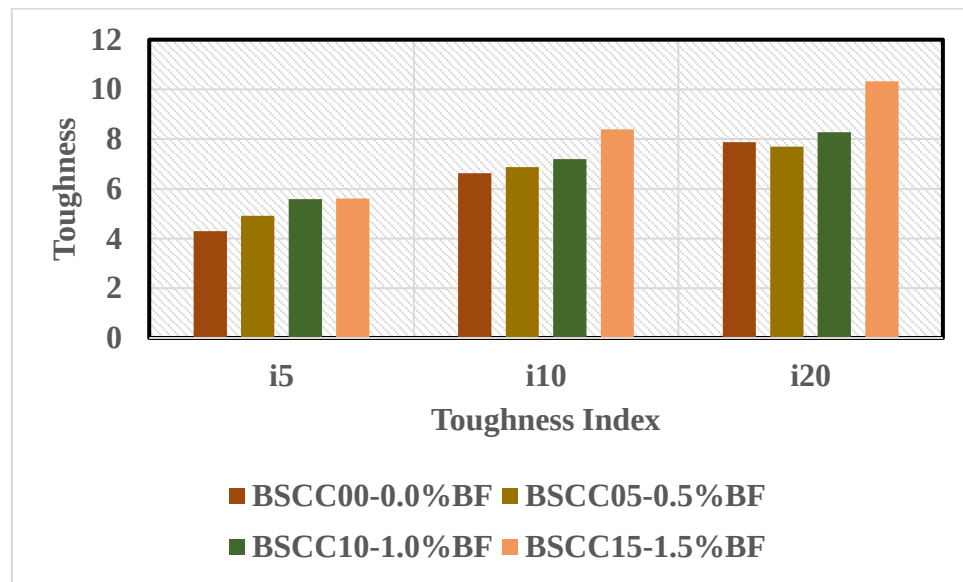


Figure 54 Toughness indices of BFR-SSSC at different BF content at 28 days.

Results show that increasing BF content highly affects the toughness of SSSC indicating that higher BF improves SSSC energy absorption capacity and enhances its resistance to impact where at 1.5% BF content, I5, I10, and I20 toughness indices increased by 30.7%, 26.4% and 31.2% respectively compared to SSSC with no BF content.

Toughness increase is due to the reason that BF provides ductility and crack bridging for the concrete mix.

4.2.3.2 BRF-SSSM Deflection and Toughness

Measuring the deflection at the center of the 28-day specimens when the four-point loading is applied, where the deflection at the maximum load and the maximum deflection before total failure are listed in **Table 40**.

Table 40 BFR-SSSM specimen average deflection under four-point loading at 28-day age.

Mix ID	BF	Peak load	Deflection at Peak load	Increase/Decrease	deflection Ultimate	Increase/Decrease
	[%]	[kN]	[mm]	[%]	[mm]	[%]
BSMM00	0.0	3.36	0.089	-	0.824	-
BSMM05	0.5	4.15	0.093	+4.5%	1.300	+57.7%
BSMM10	1.0	4.42	0.077	-13.5%	1.525	+85.0%
BSMM15	1.5	4.65	0.107	+20.2%	1.815	+120.2%
BSMM20	2.0	4.55	0.105	+18.0%	1.645	+99.5%

The average load-deflection curves of BFR-SSSM specimens are shown below for each mix at 28-day age.

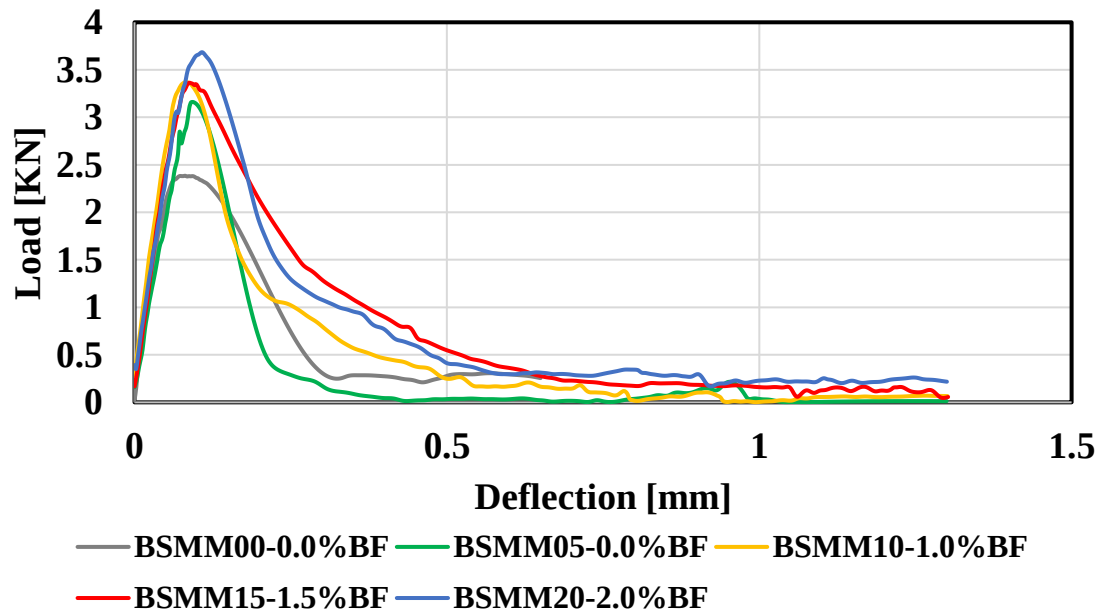


Figure 55 Load-deflection average curves of BFR-SSSM at 28-day age.

In order to calculate toughness using load-deflection curves, it is essential to calculate values related to the first crack deflection. Here, the deflection indices to be studied are I5, I10 and I20. Therefore, values of deflection at δ , 3δ , 5.5δ , and 10.5δ are calculated for each mix and represented in **Table 41**.

Table 41 Values of δ to calculate toughness

Mix ID	BF	δ	3δ	5.5δ	10.5δ
	[%]	[mm]	[mm]	[mm]	[mm]
BSMM00	0.0	0.0609375	0.182813	0.335156	0.639844
BSMM05	0.5	0.072222	0.216666	0.397221	0.758331
BSMM10	1.0	0.060639	0.181917	0.333515	0.63671
BSMM15	1.5	0.071759	0.215277	0.394675	0.75347
BSMM20	2.0	0.06745	0.20235	0.370975	0.708225

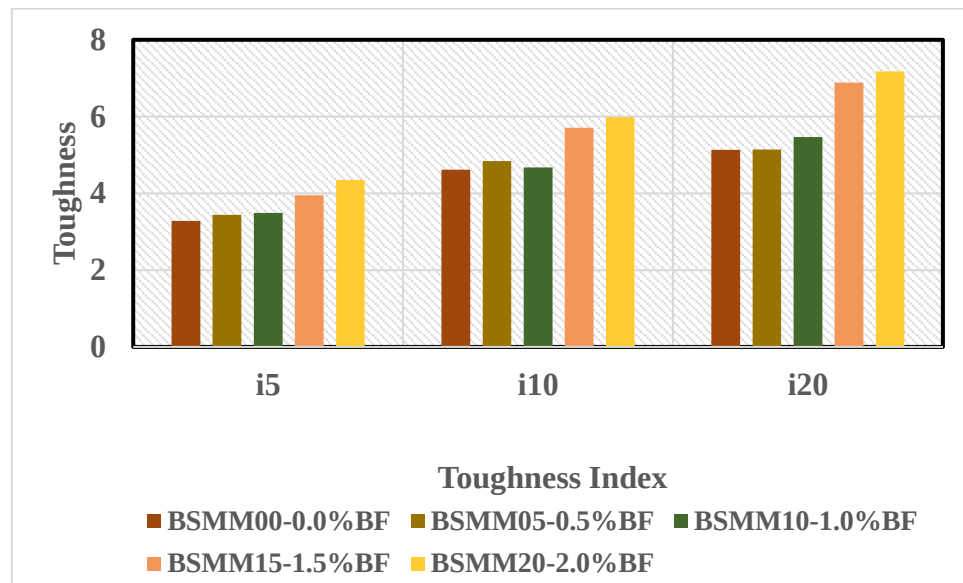


Figure 56 Toughness of BFR-SSSM at different BF content at 28 days.

Same case with SSSC, results show that increasing BF content highly affects the toughness of SSSM indicating that higher BF improves SSSM energy absorption capacity and enhances its resistance to impact where at 2.0% BF content, I5, I10, and I20 toughness indices increased by 32.5%, 30.0% and 40.0% respectively compared to SSSM with no BF content. Toughness increase is due to the reason that BF provides ductility and crack bridging for the concrete mix.

4.2.4 BRF-SSSM Drying Shrinkage.

Calculating the drying shrinkage of BFR-SSSM for a period of 90 days from curing shows that basalt fiber content enhances the ability of seawater sea sand mortar to resist shrinkage by an average of 41% and 31% at 7 days 90 days age respectively. **Table 42** shows the increase of drying shrinkage resisting of different dosages of basalt fibers at different ages.

Table 42 Drying shrinkage decrease with BF content compared to control.

BF content (%)	Age (days)								AVERAGE
	0	7	14	28	35	42	49	90	
0.0	-	-	-	-	-	-	-	-	-
0.5	0	6%	4%	5%	6%	6%	6%	6%	6%
1.0	0	12%	6%	13%	13%	14%	15%	14%	12%
1.5	0	22%	19%	20%	21%	22%	22%	23%	21%
2.0	0	41%	29%	29%	29%	29%	29%	30%	31%

Following **Figure 57** shows the drying shrinkage for different basalt fiber contents at different ages of BFR-SSSM specimens.

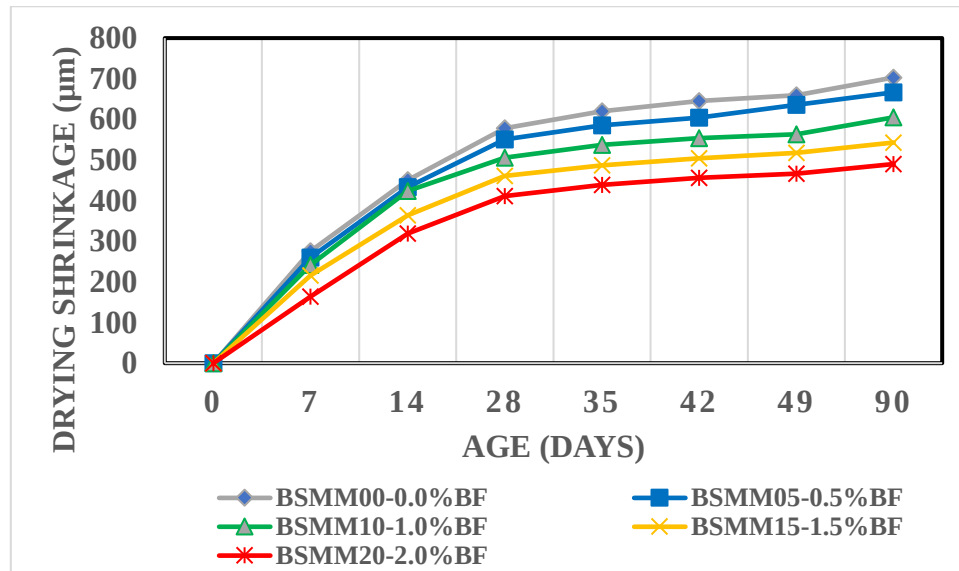


Figure 57 BFR-SSSM drying shrinkage.

Results show that the addition of BF can enhance the ability of SSSM to resist drying shrinkage significantly, reducing it by 30% when 2.0% BF content is used compared to SSSM with 0% BF content. The main reason behind this is the increased toughness of the mortar with the addition of BF.

4.2.5 BFR-SSSC Water Absorption

After testing the BFR-SSSC specimens the values are corrected using correction factor formula stated by BS 1881-Part 122 which is shown below as **Eq.4.1**

$$CF = \frac{Volume}{Surface Area \times 12.5} \quad (4.1)$$

Where both volume and surface area are in mm³, and the surface area is for the whole specimen.

Calculated average values of the water absorption and corrected water absorption are listed in **Table 43** and visualized in **Figure 58**.

Table 43 Water absorption of BFR-SSSC at 90-day age.

Mix ID	Average Water Absorption at 30 min. (90 days)	Average Corrected Absorption (1.091)	Increase/decrease
	[%]	[%]	[%]
BSC00	2.2 ± 0.20	2.4	-
BSC05	2.2 ± 0.24	2.2	-7.0%
BSC10	2.0 ± 0.14	2.2	-8.6%
BSC15	1.8 ± 0.21	2.0	-18.4%

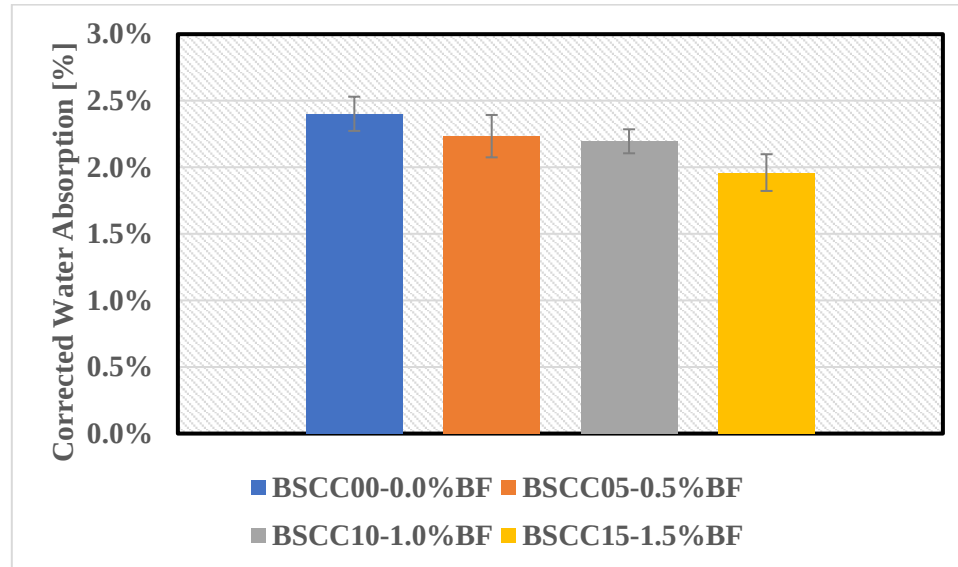


Figure 58 Water absorption of BFR-SSSC at 90-day age.

Results show that basalt fiber 1.5% addition reduces the water absorption of SSSC by an average of 18.4%. Which indicates higher durability in BFR-SSSC compared to SSSC without inducing basalt fibers to the mix.

4.3 Microstructure and Phase Identification

4.3.1 SEM-EDS

The following figures show different hydration products including calcium hydroxide (CH), calcium silicate hydrates (CSH), ettringite. In addition, basalt fibers are shown in some figures along with Friedel's salt crystals. The presence of Friedel's salt is due to the usage of seawater in the mix, which makes the cement matrix more defined and well compacted when compared to concrete mixed with freshwater.

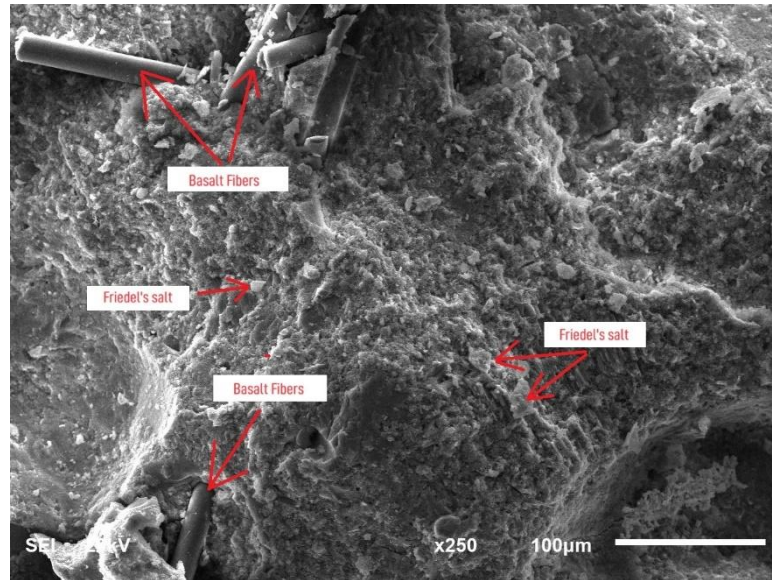


Figure 59 BFR-SSSM specimen under SEM at x250 magnification.

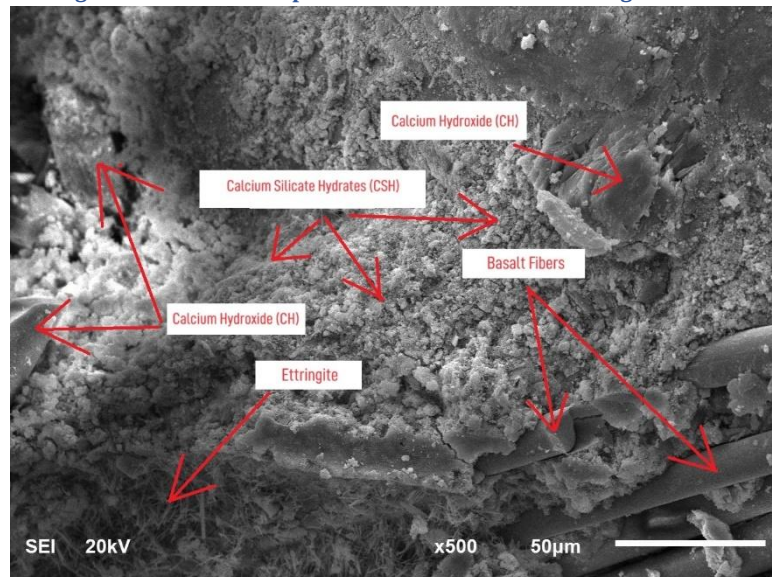


Figure 60 BFR-SSSM specimen under SEM at x500 magnification.

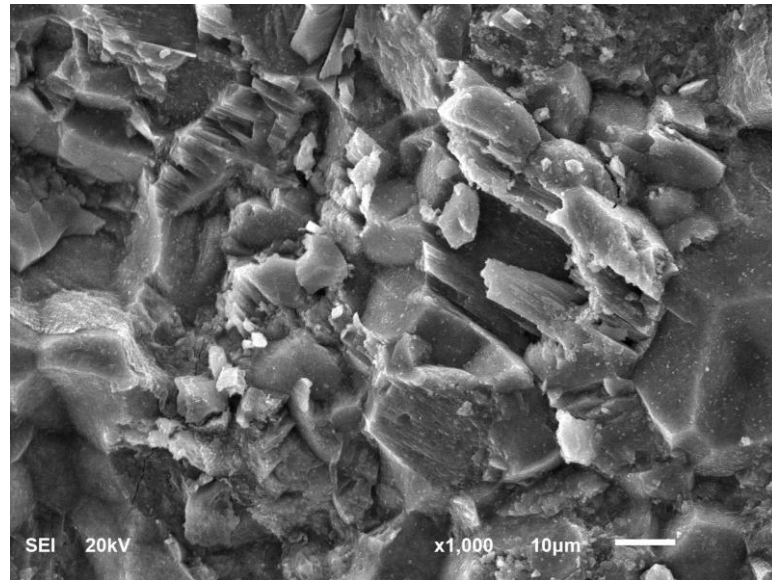


Figure 61 BFR-SSSM specimen under SEM at x1000 magnification.

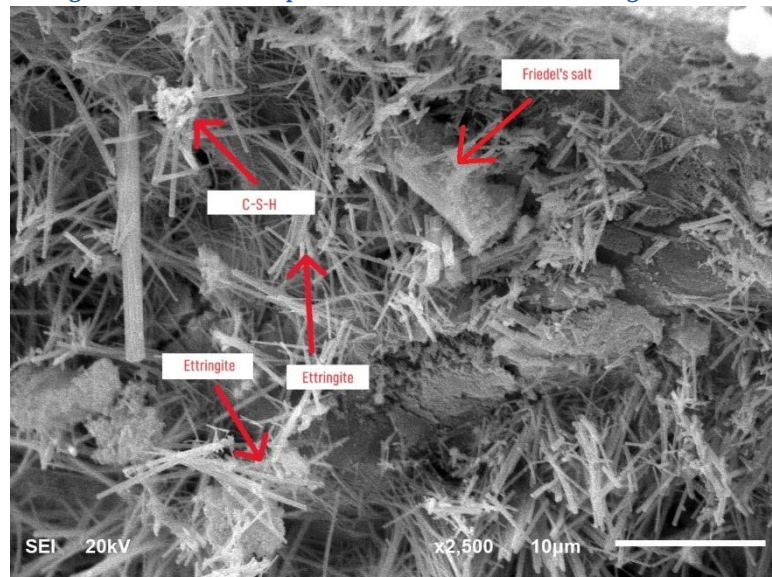


Figure 62 BFR-SSSM specimen under SEM at x2500 magnification.

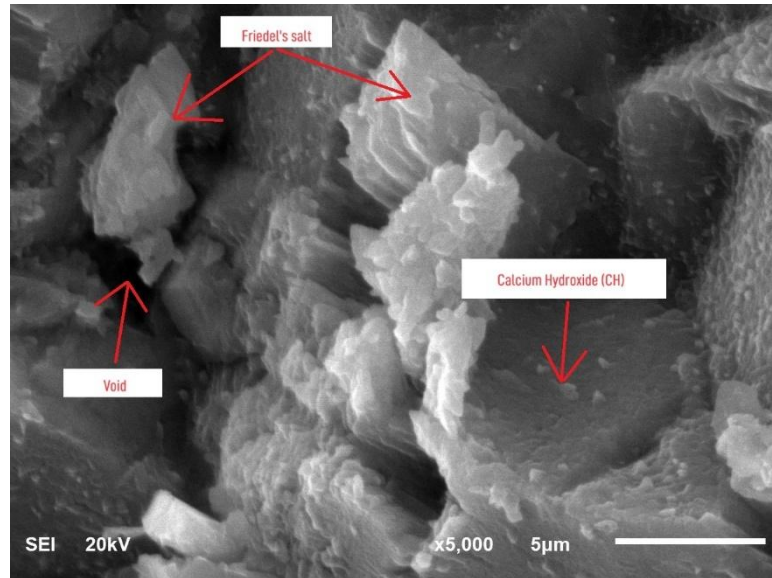


Figure 63 BFR-SSSM specimen under SEM at x5000 magnification.

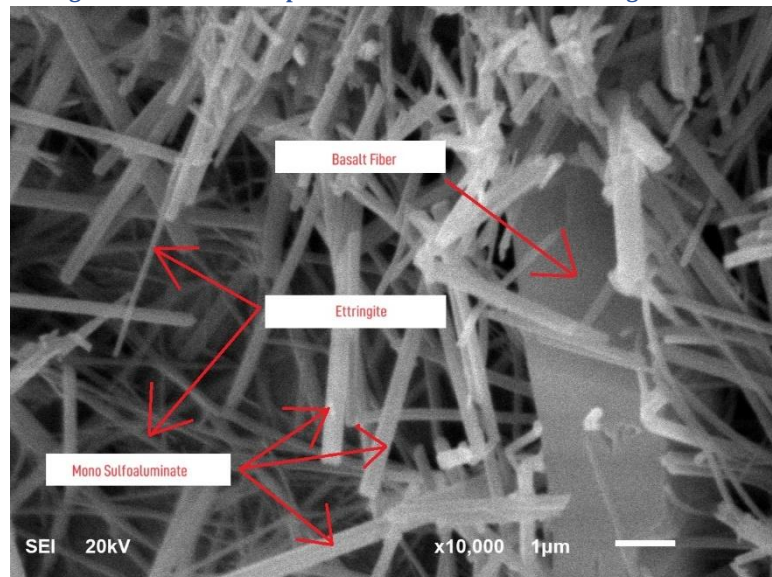


Figure 64 BFR-SSSM specimen under SEM at x10000 magnification.

Following **Figure 65** shows the EDS analysis spectrum for some areas of the BFR-SSSM specimens under SEM machine.

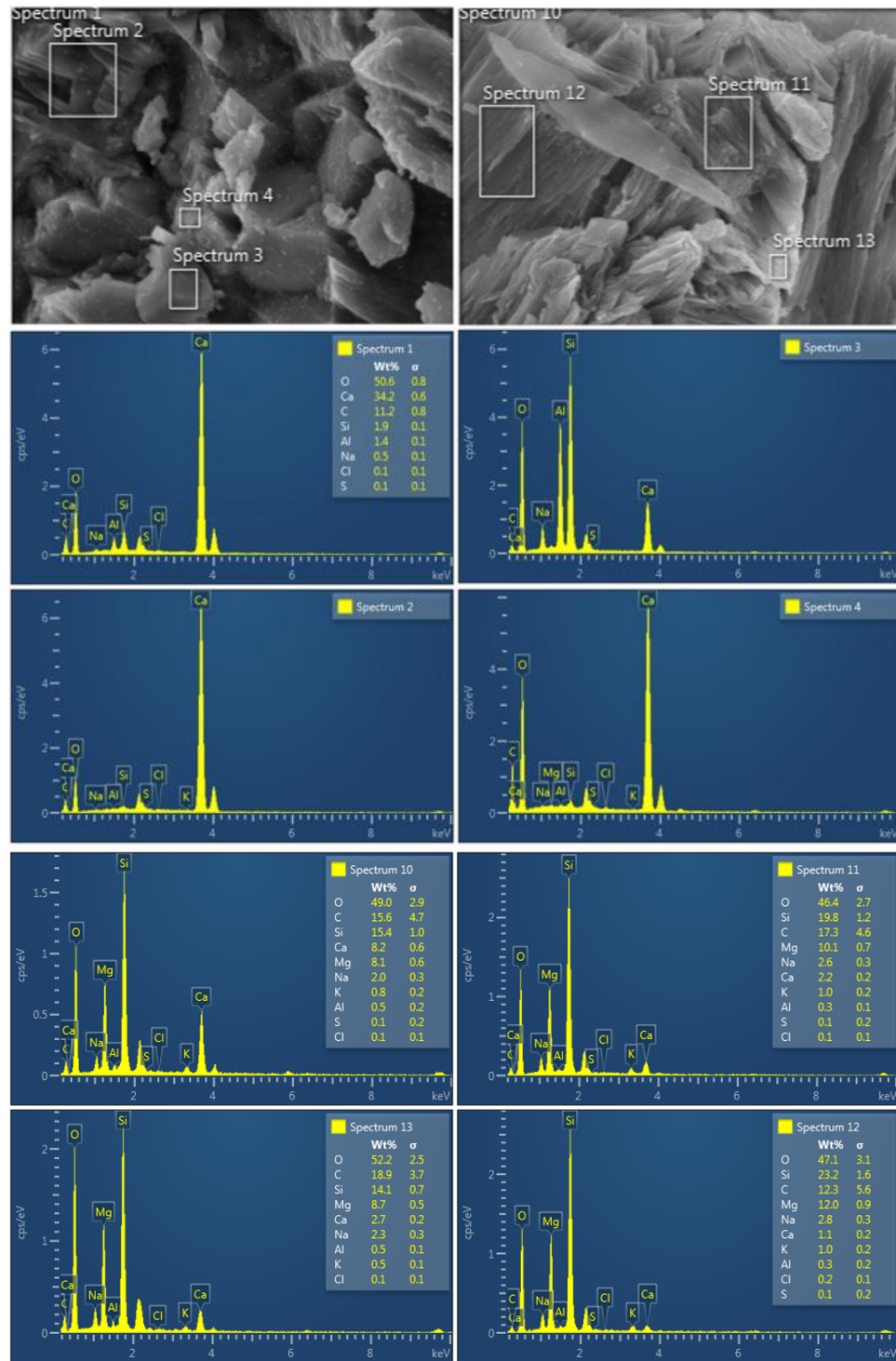


Figure 65 EDS analysis spectrum for some areas of the BFR-SSSM specimens under SEM machine

4.3.2 XRD

4.3.2.1 Seawater Sea Sand Mortar (SSSM)

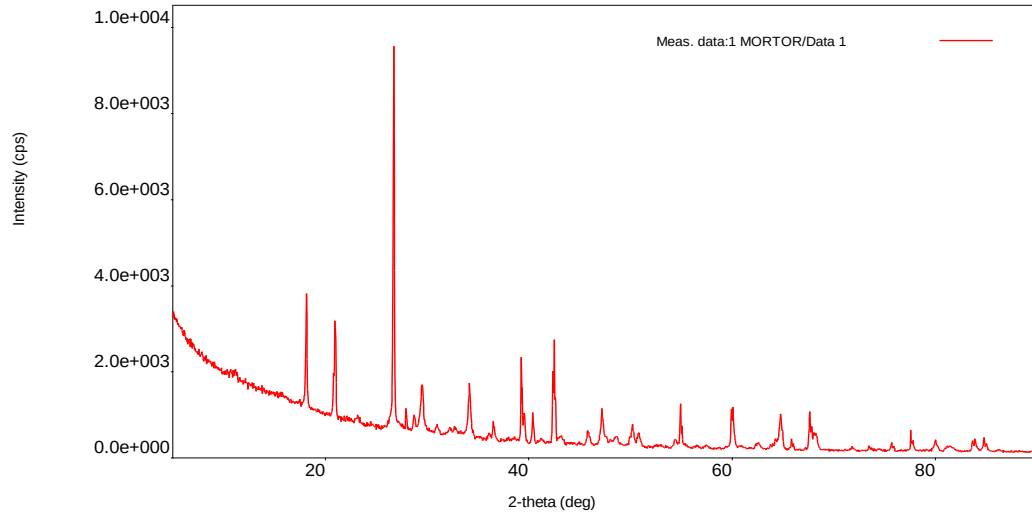


Figure 66 XRD Analysis of SSSM specimen at 20

4.3.2.2 Seawater Sea Sand Concrete (SSSC)

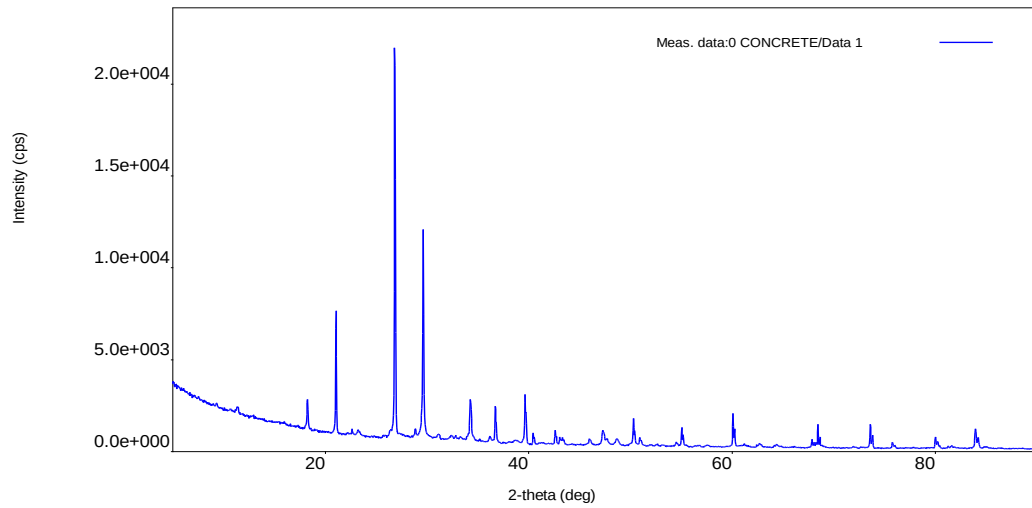


Figure 67 XRD Analysis of SSSC specimen at 20

Analyzing and identifying the peaks of the previously shown graphs shows presence of quartz which is a main component of sea sand, it also shows portlandite and calcite as hydration products. **Figure 68** shows the peaks identification of XRD for both SSSC and SSSM samples.

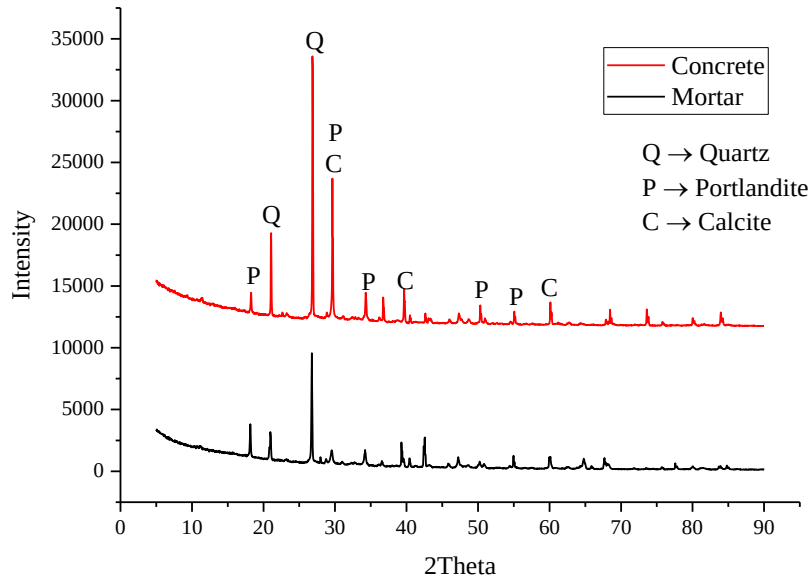


Figure 68 Identified peaks of XRD for both SSSC and SSSM samples.

4.4 Conclusions

In this research, green cementitious mixes are introduced where basalt fibers (BF) are used to reinforce seawater sea sand concrete (SSSC) and seawater sea sand mortar (SSSM). Seawater, sea sand, and basalt fibers are used as alternatives to fresh water, normal sand, and steel fiber respectively, where the latter materials are mostly more expensive, more valuable, and are heavily demanded in many industries alongside the construction industry. This research is conducted to study the mechanical behavior, microstructure, and durability of SSSC and SSSM reinforced with different basalt fiber content.

- **Workability:** Results showed that BF content highly affects the workability of SSSC, where the super-plasticizing agent must be used in the concrete mix. BF content cannot be further increased beyond 2.0% for SSSM and 1.5% for SSSC.
- **Initial and Final Setting Time:** BF content does not significantly affect the initial setting time nor the final setting time of SSSM.
- **Compressive Strength:** BF content increased compressive strength of SSSM peaking at 17.1% at 1.0% BF content compared to control group, while slightly decreasing compressive strength of SSSC where 11.0% decrease in compressive strength of SSSC is observed at 1.5% of BF content compared to control group.
- **Modulus of Elasticity:** BF content increased modulus of elasticity of SSSC showing 29% increase in Elasticity at 1.5% BF content compared to control group.
- **Density of BFR-SSSC:** BF content has no noticeable effect on SSSC density, where a 7% decrease in density is showing at 1.5% BF content compared to control group.

- **Flexural Strength:** BF content highly increases the flexural strength of SSSM where an increase of 42%, and 39% in flexural strength is observed at 1.0% BF content compared to control group. In addition, BF content increased flexural strength of SSSC by 70% at 1.5% BF content compared to control group.
- **Split Tensile Strength:** BF content highly affect the split tensile strength of BFR-SSSC where an increase of 80% is observed at 1.5% BF content compared to control group.
- **Toughness:** BF content increased toughness significantly for both SSSC and SSSM where I5, I10, and I20 toughness indices increased by for SSSC by 32.5%, 30.0% and 40.0% respectively at 1.5% BF content , and for SSSM 32.5%, 30.0% and 40.0% respectively at 2.0% BF content compared to control.
- **Drying Shrinkage:** Results show that the addition of BF can enhance the ability of SSSM to resist drying shrinkage significantly, reducing it by 30% when 2.0% BF content is used compared to SSSM with 0% BF content at 90 days.
- **Water Absorption:** BF 1.5% addition to SSSC reduces the water absorption of SSSC by an average of 18.4% at 90-day age.
- **SEM and XRD:** Both SEM-EDS and XRD analysis are done to the BFR-SSSC and BFR-SSSM specimens. The analysis showed well-compact and healthy microstructure.

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