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MECHANICAL AND DURABILITY PROPERTIES OF GLASS FIBER REINFORCED CONCRETE

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Bahadur AMED

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Dedicated to my family

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LIST OF SYMBOLS

F_{LOP}	Load at limit of proportionality, in newtons
F_{MOR}	Failure load, in newtons
l	length of test piece, in millimeters
l_0	Distance between the pads measured at the beginning of the test, in micrometers
l_1	Distance between the pads measured after 96 h immersion, in micrometers
l_2	Distance between the pads measured after 21 days drying in the Oven and 6 hstabilization, in micrometers
L	Span, in millimeters
Δ_{LOP}	deflection at limit of proportionality, in millimeters
Δ_{MOR}	deflection at failure, in millimeters
ε_{LOP}	Deformation at limit of proportionality
ε_{MOR}	Deformation at failure
σ_{LOP}	Stress at limit of proportionality, in megapascals
σ_{MOR}	Stress at failure, in megapascals
$\frac{\Delta l_s}{l}$	Value of residual shrinkage, in millimeters per meter
$\frac{\Delta l_e}{l}$	Value of expasion, in millimeters per meter
$\frac{\Delta l_c}{l}$	Value of extreme dimensional variation, in millimeters per meter
m_w	Mass of a test piece after drying, ‘dry mass’, in grams
m_d	Mass of a test piece after immersion, ‘wet mass’, in grams
p	Porosity, in percentage by mass
ρ_d	Dry density, in kg/m^3

γ	Water absorption by immersion, in percentage by mass
V	Volume of a test piece, in cm^3
w/b	Water to binder ratio

LIST OF ABBREVIATIONS

AR	Alkali Resistant
CH	Calcium Hydroxide AR
CSH	Calcium Silicate Hydrate
GFRC	Glass Fiber Reinforced Concrete
LOP	Limit of Proportionality
MOR	Modulus of Rupture
OPC	Ordinary Portland Cement
PVA	Polyvinyl Alcohol
RH	Relative Humidity
RHPC	Rapid-Hardening Portland Cement
SEM	Scanning Electron Microscopy

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ABSTRACT

Mechanical and Durability Properties of Glass Fiber Reinforced Concrete

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Department of Civil Engineering

Master of Science Thesis

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Glass fiber reinforced concrete (GFRC) is a composite material generally used as a precast exterior element in the construction sector. GFRC is a material which is typically composed of cement, sand, water and glass fibers. The use of high amounts of cement in GFRC affects the long-term durability of the material. Cement production causes high energy consumption and CO_2 emissions. In this study, the effect of replacing cement with fly ash and blast furnace slag was investigated with the specific aim to reduce cement content and obtain a more environmentally friendly material. For this purpose, 12 different GFRC mixtures were produced and their physical, mechanical, and durability properties were investigated by replacing cement at a fixed ratio of 50% with fly ash and blast furnace slag. GFRC mixes were exposed to freeze-thaw cycles, wet-dry cycles, and high-temperature effects to determine their durability. In addition, SEM micrographs were taken to determine the microstructure of the samples taken from the concrete mixes. Test results showed that the replacement of cement with fly ash and incorporation of acrylic polymer significantly increased the workability. The water absorption and the apparent porosity values of the

mixtures varied between 8-12% and 16-24% respectively, and their dry densities varied between 1870 and 2018 kg/m^3. Replacement of cement with pozzolanic materials reduced the extreme dimensional variations compared to reference mixes, the values varied between 1.08 and 1.47 mm/m. Although substitution of cement with fly ash and slag reduced the early age strength, the flexural strength improvement ratio of the mixes with pozzolanic materials with age and with the increase of glass fiber content were found to be higher than those of the reference mixes. The highest flexural strength was observed in C100PG3 mix as 15.1 MPa at 90 days and the highest flexural strength improvement was observed in F25S5PG4 mix as 93% at 28 days by an increase in fiber content from 0% to 4%. The mixes incorporating pozzolanic materials showed better performance in durability tests. The exposure to freeze-thaw cycles improved the flexural strength of GFRC mixes. The flexural strength of mixes incorporating pozzolanic materials increased up to 39% after the freeze-thaw cycles. The wet-dry cycles, on the other hand, caused dramatic loss of strength. However, mixes incorporating pozzolanic materials performed better and the loss of the strength was decreased compared to the reference mixes. The high temperature exposure caused significant loss in flexural strength of the mixes. Acrylic polymer addition and the increase in fiber content reduced the durability against high temperature.

Keywords: Glass fiber reinforced concrete, fly ash, slag, durability, sustainability, microstructure, mechanical properties, physical properties, SEM analysis

ÖZET

Cam Elyaf Takviyeli Betonun Mekanik Ve Durabilite Özellikleri

Bahadur AMED

İnşaat Mühendisliği Bölümü

Yüksek Lisans Tezi

Danışman: Doç. Dr. Nihat KABAY

Cam elyafı takviyeli beton (CETB) inşaat sektöründe prekast dış cephe elemanı olarak kullanılan kompozit bir malzemedir. CETB, genellikle çimento, kum, su ve cam elyaf karışımından oluşur. CETB'de yüksek miktarda çimento kullanılması malzemenin uzun vadeli durabilitesini etkiler. Çimento üretimi yüksek enerji tüketimine ve CO_2 emisyonuna neden olduğundan bu çalışmada, çimento kullanımını azaltmak ve çevre dostu bir ürün elde etmek için çimentonun uçucu kül ve yüksek fırın cürufu ile ikame edilmesinin etkileri araştırılmıştır. Bu amaçla üretilen 12 farklı CETB karışımında çimento %50'ye kadar uçucu kül ve yüksek fırın cürufu ile ağırlıkça ikame edilmiş ve fiziksel, mekanik ve durabilite özellikleri araştırılmıştır. CETB karışımları, durabilite özelliklerini belirlemek amacı ile donma-çözülme çevrimlerine, ıslanma-kuruma çevrimlerine ve yüksek sıcaklık etkilerine maruz bırakılmıştır. Ayrıca, beton karışımlardan alınan örneklerde içyapı özelliklerimi belirlemek amacıyla SEM görüntüleri alınmıştır. Deney sonuçlarından elde edilen verilere göre çimentonun uçucu kül ile ikamesi ve akrilik polimer kullanılması işlenebilirliği önemli ölçüde artırmıştır. Karışımların

su emme oranı ve porozitesi sırasıyla 8-12% ve 16-24% arasında ve kuru yoğunlukları 1870 ile 2018 kg/m^3 arasında değişmiştir. Toplam boyutsal değişimler 1,08 ile 1,47mm/m arasında değişmiş, çimentonun puzolan malzemelerle ikame edilmesi toplam boyutsal değişimleri referans karışımlara kıyasla azaltmıştır. Çimentonun uçucu kül ve cüruf ile ikamesi erken dayanımı düşürmesine rağmen puzolan katkılı serilerin eğilme dayanımındaki artış oranı kür süresi ve lif oranındaki artış ile birlikte referans serilere oranla daha yüksek olmuştur. En yüksek eğilme dayanımı C100PG3 serisinde 90 günde 15.1 MPa olarak belirlenmiş ve en yüksek eğilme dayanımı gelişimi lif oranının %0'dan %4'e artması ile F25S25PG4 serisinde 28 günde %93 olarak tespit edilmiştir. Puzolan malzeme içeren seriler durabilite deneylerinde daha iyi performans göstermiştir. CETB serilerin eğilme dayanımı donma-çözünme etkisi altında beklenmedik şekilde artmıştır. Puzolan malzeme içeren serilerin eğilme dayanımı donma-çözünme çevrimleri neticesinde %39'a kadar artmıştır. Islanma-kuruma çevrimleri ise dayanımda ciddi düşüşlere yol açmıştır. Ancak puzolan malzeme içeren seriler daha iyi performans göstermiş ve bu serilerde dayanımdaki düşüş referans serilere göre daha az olmuştur. Yüksek sıcaklık beton serilerde ciddi dayanım kaybına yol açmış, akrilik polimer ve lif oranındaki artış yüksek sıcaklığa dayanıklılığı olumsuz yönde etkilemiştir.

Anahtar kelimeler: Cam elyaf takviyeli beton, uçucu kül, cüruf, durabilite sürdürülebilirlik, içyapı, mekanik özellikler, fiziksel özellikler, SEM analizi

1 Introduction

1.1 Literature Review

Glass fiber reinforced concrete (GFRC) is a material used in large areas in the construction sector, where matrix and reinforcement can be considered as separate composites. GFRC has disparate structure from conventional cement-based composites, especially concrete and steel reinforced concrete. In general, use of fibers as the reinforcement in GFRC, the nature of stress transfer between the fiber-matrix and the types of failure, separates the GFRC from other cement-based composites [1]. GFRC is a multiphase material, composed of a continuous matrix phase and a discontinuous AR-Glass fiber reinforcement phase [2].

The cement-based matrix generally consists of cement and aggregate and the fibers are dispersed in this mortar. In this form of combination, matrix and fibers retain their own chemical and physical properties and combine the best properties of both that cannot be obtained by these materials alone. In general, the fibers improve the flexural strength and ductility of the matrix, while the matrix provides load transfer between the fibers. Thereby, a material is achieved with high tensile strength and improved ductility [3], [4].

Plain, non-reinforced brittle cementitious materials are qualified with their low tensile strength and low tensile strain. Therefore, they require reinforcement in order to be used as a construction material. Traditionally, reinforcements are regularly placed in areas of concrete exposed to tensile and shear forces [5]. On the other hand, reinforcing the cementitious matrix in GFRC cannot be achieved by a prearranged positioning as in ordinary reinforced concrete. The reinforcement in the GFRC generally consists of a different number of fibers and bundles of different lengths and shapes. These fiber reinforcements are randomly

dispersed in the matrix [1]. Therefore, they cannot be regarded as suitable materials to withstand the tensile stresses. However, the fact that they are dispersed in the matrix at lesser intervals than conventional steel reinforcements put forward the fibers in keeping the cracks under control. For this reason, fiber reinforcement offers better performance rather than traditional steel bar reinforcement for thin-thickness construction components and for high-load or deformation-resistant tunnel linings and explosion-proof structures [5].

GFRC has been used for the last half century owing to its good mechanical properties, good fire resistance, moldability and resistance to corrosive processes [6]. As a result, GFRC has a wide range of applications such as permanent formwork for building restorations, in sewer liners and in tunnel cladding, riverside protection walls and as acoustic barriers [6]–[11].

The most important problem encountered with the use of GFRC material is the deterioration of mechanical properties with age [4], [12], [13]. According to many researchers, this is due to the fact that the high alkaline environment of cement mortar corrodes and cause fragility in glass fibers with time. In an attempt to overcome this problem, AR-glass fiber was developed [4], [5], [9], [14]. AR-glass fiber improves the mechanical properties and durability of GFRC such as compression and bending strength. However, exposure to ageing reduce the durability of GFRC and even affects the stability of glass fiber [2].

The durability problem of GFRC is explained by three different mechanisms [5], [9], [15]. The first is explained by the corrosion of fibers by hydroxyl ions derived from hydration of the cement matrix [15]–[17]. The second is explained by the precipitation of hydration products on the surface of the fiber, reducing fiber elasticity, as well as changing the failure mode from pullout to fiber fracture by increasing the adherence between the fiber and the cement matrix. The third is expressed by the formation of a more dense matrix structure at the interface and decreasing of the flexibility [15].

In order to overcome the effects of GFRC's ageing process, improvements in alkaline resistant glass fiber have been made and new cement matrices have been

developed [15], [18]–[20]. Improvements in the cement matrix are based on the use of Portland cement with a number of additions such as blast furnace slag, fly ash, silica fume and metakaolin. With the use of these additives, it is aimed to reduce or eliminate the calcium hydroxide (CH) formation due to the ageing process and to reduce the pH of the pore solution. Recent studies have shown that such improved matrices are effective in maintaining basic mechanical properties such as tensile strength and durability in conventional accelerated ageing tests [15], [16], [21], [22].

According to an experimental study, when cement is replaced with pozzolanic materials, such as fly ash, rice husk ash, and palm fuel ash up to 20%, the properties such as bending strength and durability are improved [16]. According to Peled and Jones [17], the use of dimension-stabilizing admixture (NSR) and slag in certain proportions instead of cement improves the long-term durability of GFRC. These studies are supported by effective mechanical, physical and durability test results and substitution of cement with additives has shown good results in GFRC. However, there is a lack of study in the literature on the use of pozzolanic materials such as fly ash and slag at higher ratios. Also, more research is needed to determine the durability of this material, especially its resistance to elevated temperatures. The use of supplementary cementitious materials in higher ratios should be aimed due to benefits in durability properties and in order to make the GFRC an environmentally friendly material with less cement content.

1.2 Objective of the thesis

In the production of GFRC, generally large amount of cement is used. Corrosion of the fibers, reduction of the flexibility of the fibers by hydration products of cement matrix, hence deterioration of the mechanical and durability properties of the GFRC necessitate the use of mineral additions. In addition, the production phase of the cement consumes a large amount of energy and produces CO_2 gas which affects the environment. For the reasons mentioned, any attempt to reduce the use of cement brings several advantages in terms of cost and sustainability. In

this study, a detailed experimental work was carried out to investigate the effect of substitution of cement with fly ash and blast furnace slag on the strength development and durability properties of GFRC mixtures.

1.3 Hypothesis

Industrial waste materials are generally used in traditional concrete to improve long term strength and durability properties. Since the GFRC material has long-term durability issues, the use of pozzolanic materials will help contribute its long-term performance in the field exposed to natural environmental conditions such as wet-dry and freeze-thaw.

2
Glass Fiber Reinforced Concrete

2.1 Description and Brief History of GFRC

GFRC is a composite material composed of hydraulic cement, sand, alkaline resistant glass fiber, and water. Reinforcing with glass fiber improves tensile and bending characteristics of the cement mortar. The fact that GFRC can be produced in attractive, durable, light and complex shapes and profiles has provided their intensive use on the exterior of the buildings. The biggest advantage of GFRC is that it is light compared to other precast concretes. As a result, it offers lower transport, handling and installation costs. The structural advantages of GFRC are its durability, chemical resistance, fire resistance, impact resistance and good sound and heat thermal insulation properties [23].

The first attempts to improve the ductility of the naturally brittle material by integration of strong, stiff fibers have been made thousands of years ago. In the first practical applications, hard, dry clay was reinforced with straw and other natural fibers to convert it to a more ductile material. Therefore, the use of fiber-reinforced composites in the construction area is nothing new. However, high-performance, cement-based, fiber-reinforced composites were not used at the construction sites until the invention of asbestos cement at the end of the nineteenth century [1].

Borosilicate type E-glass was developed with advances in glass fiber production at the beginning of the twentieth century and the first polymer entered industrial production. The increase in availability of different fiber types after the World War II encouraged the development of new fiber-reinforced composites containing cement-based matrices. The first GFRC was produced in the USSR at the end of the 1950s, based on E-glass fibers combined with non-alkali matrices [1], [24]. Since the alkaline environment causes loss of corrosion and tensile strength in E-

glass fibers, ordinary Portland cement could not be used as matrix material. As a result, GFRC production was limited in its early years. Although it had special glass formulations that provided alkali resistance, it was not possible to obtain GFRC commercially until the late 1960s. Alkaline resistant fiber, Cem-Fil fiber, was developed as a commercial product by a joint research project of a team led by A.J. Majumdar at UK Building Research Station and A. Tallentire at Pilkington Glass Co [25]. At the same time, Japanese glass manufacturers Nippon Electric Glass Co. (NEG) and Asahi Glass Co. (AGC) developed commercial production of AR fibers with high ZrO_2 content. In spite of these developments, GFRC exposed to humid environment experienced loss of ductility due to ageing process [1].

To address this problem, manufacturers of AR-glass fiber have developed new generation fibers with different surface treatments that significantly improve their long-term performance in ageing in a humid service environment such as CemFil2 AR-fibers in the early 1980s. It has also been an alternative to replacing the cement in the GFRC matrix with low amounts of acrylic polymer to obtain a more durable composite [1], [26], [27].

With the construction boom in the world at the beginning of the new millennium, there was a rapid increase in the production of GFRC and GFRC has been recognized as a high-tech material in the world of construction sector [1].

2.2 Constituent materials

The materials used in the production of GFRC are generally cement, sand, water and additives. Recently, it is becoming more common to replace cement by different pozzolanic materials. In this section, the materials used in GFRC are mentioned in detail.

2.2.1 Binders

Hydraulic cement is generally used as binder in GFRC manufacturing. Hydraulic cement, especially the Ordinary Portland cement (OPC), produce calcium

hydroxide (CH) during hydration and this alkaline environment continues throughout the service life of GFRC. In order not to affect the durability of the GFRC, the choice of cement should be coordinated with the fiber to be used. Types of Portland cement can be used together with AR-glass fiber to eliminate the effects of the alkaline environment. In GFRC, except for OPC, rapid-hardening Portland cement (RHPC) and white Portland cement are used [1], [23]. The difference between RHPC and OPC is fineness of the particles and lime content. RHPC can reach 7-day strength of OPC in 3 days. White Portland cement is made of raw materials with low iron content. White Portland cement is generally used as a binder when white or light-colored surface finish is desired.

The use of pozzolanic materials reduces the effects of the alkaline environment, and also improves the bond between the matrix and the glass fiber. Pozzolanic materials are generally used by substituting cement in certain proportions. The use of pozzolanic materials is very critical in the construction sector, they help reduce the use of cement and contribute to sustainability. The pozzolanic materials react with hydrated calcium hydroxide to improve the nature and microstructure of cement matrix in glass fiber concrete. Thus, the mechanical properties and durability of GFRC are improved [28]. Fly ash, which is one of the wastes of carbon thermoelectric power plants, is one of the pozzolanic materials used for this purpose. Fly ash is a good pozzolanic material that reacts with portlandite in medium and long curing times and increases resistance and workability and reduces the hydration temperature of Portland cement [2].

The other material used in GFRC production is blast furnace slag, which is a byproduct of iron production. The use of slag improves the long-term performance of concrete as well as durability and reduces the negative effects of cement on the environment. According to Mills [29], the strength of GFRC produced by substituting cement with slag up to 50% is equivalent to the strength of matrix after 2 years of ageing.

The cement used in the production of GFRC must comply with local or international standards. In GFRC, cement of CEM I - CEM V standards are used.

2.2.2 Aggregates

In the early days of GFRC, the use of aggregates was either kept very low or not at all. The matrices were generally produced from a large amount of cement. For this reason, it was called glass fiber cement. The use of aggregate has increased after realizing that the cost of the matrix could be reduced and some of its properties could be improved by the use of fine aggregates [1].

The aggregate to be used in the GFRC should preferably be round or irregular and smooth. The particle size of the aggregate should not exceed 1.2 and 2.4 mm in the spray and premix GFRC, respectively. For spray and premix production methods, the amount of fine grain retained over 150-micron sieve should not exceed 10%. Silica sand with silica content greater than 96% is generally used in the production of GFRC. Moisture content of fine aggregates should be lower than 2%. Fine aggregate should be cleaned from organic matter and its loss on ignition should be lower than 0.5%. It should also be free of soluble salts [23].

2.2.3 Fibers

The fibers are the main components of the GFRC, which take the major part of the acting load. Fiber type, ratio, length, and orientation affect the density, tensile strength, fatigue strength and failure mechanism of the composite [30].

Glass fibers are produced in a process in which molten glass is exuded through several orifices in the form of filaments from the bottom of a heated platinum tank or bushing. Generally, 204 filaments are drawn simultaneously. The drawn filaments become solid when cooling outside the heated tank [31], [32]. Then, 204 filaments are collected into a strand on a drum. The filaments are coated with a sizing that protects them against weather and abrasion effects, and several strands are wound together to form a roving [5]. The coating affects the chemical and mechanical interaction between the fibers and the matrix, as well as the individual fibers within a strand. Different coatings can be made according to the production method used. In applications where low fiber content is used and the maximum degree of dispersion into individual fibers is desired, fibers with a

water-soluble coating are used to help strands split into individual filaments. This application aims to reduce the micro-cracking of decorative mixtures. On the other hand, the distribution of glass fibers in GFRC usually consists of many filaments in bundles [1].

The glass fiber content is generally given as percentage of the total weight of the GFRC composite. Glass fiber ratio depends on the production method; and is between 4 and 5% in the spraying method and is between 2 and 3% in the premix method. Glass fibers are often dispersed in two-dimensional (2-D) layers in the spraying process and show a three-dimensional (3-D) distribution in the premix method. Increasing the glass fiber amount above the specified values in both production method reduces workability and makes the compaction difficult [1].

All of the currently used AR glass fibers are based on a silicate glass containing zirconium dioxide (ZrO_2). The ZrO_2 content should be at least 16% to produce a durable GFRC and provide alkali resistance [1]. A typical composition of AR glass is shown in Table 2.1.

Table 2.1 Typical composition of an AR glass [1]

SiO_2	ZrO_2	Al_2O_3	CaO	Na_2O	K_2O
60-62	16-20	0.3 - 0.8	0.5 – 5.6	14 - 17	0 – 2

The length of the glass fiber strands generally does not exceed 37 mm in the spraying method and 25 mm in the premix method. It is difficult to simultaneously spray longer strands and ensure uniform distribution in the fresh matrix. The tensile strength of glass fibers is maintained up to 200°C. The strength of the glass fibers is gradually reduced at temperatures between 200 and 700°C. [1]. Typical physical and mechanical properties of AR glass fibers are shown in Table 2.2.

Table 2.2 Typical physical and mechanical properties of AR glass fibers [23]

Tensile strength (MPa)		Young's modulus (GPa)	Density (kg/m^3)	Strain at fracture (strand) (%)	Filament diameter (μm)
Single filament	Strand				
3000-3500	1300-1700	70-74	2600-2700	2.0-2.5	13-20

2.2.4 Admixtures

It is necessary to use appropriate amounts of additives to improve the properties of GFRC. Many of the additives developed and used for conventional concrete technology can also be used for GFRC [33]. Some additives are effective in the fresh state of GFRC, while others are used to improve the hardened properties of GFRC.

The most commonly used additive in GFRC are the plasticizers and the superplasticizers. These additives improve the workability of the matrix without affecting the properties of the GFRC. The materials used as plasticizers are mainly waste materials from lignosulphonates-based paper production. The superplasticizers, which are more effective than the plasticizers, distribute the cement particles and enable a more dense and strong matrix to be reached at an early age [1].

New polymer compositions with viscosity modifiers (VMA) have been developed using nano-scale molecular technology for self-compacting concrete [34]. These additives also improve the workability of the fresh GFRC mixture by self-compacting which also contributes to a better surface finish [1].

Recently, a new product has been developed in the area of GFRC that can completely replace cement. The discovery of the very high photocatalytic ability of nanoscale particles of anatase type titanium dioxide has been implicated in the development of this new material, called photocatalic GFRC or eGFRC [35]–[37]. In the first experiments, photocatalic GFRC was produced by substituting 5% of the cement with a photocatalically activated version of TiO_2 (anatase). Although

it is possible to replace the cement completely with a photocatalytic binder in the GFRC, it is not economically suitable. The advantage of the self-cleaning mechanism of eGFRC, which is activated by exposure to UV lights, can be utilized in a non-reinforced surface layer at close cost to normal GFRC [1].

Many additives have been used to improve the properties of fresh GFRC, such as improving workability, improving cohesion, reducing segregation, reducing bleeding, improving the properties of fresh GFRC, accelerating the early age strength, and improving the properties of hardened GFRC such as permeability.

These additives are generally used at low percentages of cement by weight and in appropriate amounts.

2.2.5 Polymers, Pigments and Additives

Polymer additive is used to enable dry curing and to improve early strength by eliminating the need for long-term curing of GFRC. The use of polymers has a positive effect on the properties of both fresh and hardened GFRC. Polymers generally improve the workability of the fresh mixture and affects the bond between the matrix and fiber in hardened GFRC. After several hours of addition to the mixture, the polymer also forms a layer which reduces the water permeability of the GFRC mixture. Adding high amounts such as 10% increases the ductility of the GFRC and reduces the flexibility module. At the same time, the incorporation of the polymer provides more dense and soft surface finishes.

In order to improve the properties of GFRC in general, acrylic polymer which exhibits stable behavior in alkaline environment is used. The use of acrylic polymer with water content up to 50% reduces the water requirement of the mixture in the same amount. Powder-containing polymers have a solids content of 90% to 100%. Polymers in the form of water-based dispersion are susceptible to frost damage and the temperature of the mixture should not be below 7-12 °C in the production stage in order to avoid losing the film-forming property [1].

According to the research by Ball H. [38] samples containing 7% acrylic polymer cured in a wet-dry climate for 19 years retained their toughness and samples without acrylic polymer lost their ductility and bending strength by about 40%.

Another study showed that polyvinyl alcohol (PVA) powder improves ductility and tensile strength during aging. In the microstructural analysis, it was observed that PVA powder formed a thin protective polymer film on the glass fiber surfaces [39].

Even low amounts of the acrylic polymer in powder form, such as 1% of the cement, or the equivalent liquid dispersion, are sufficient to eliminate the need for wet curing. The use of low amounts of polymer improves the long-term performance of the hardened composite by indirectly curing the fresh GFRC. However, it does not directly affect the strength and mechanical properties of GFRC [1]. Polymers to be used should comply with the specifications in Table 2.3 [40].

Table 2.3 Typical specification for acrylic polymer

Compound Type	Aqueous thermoplastic polymer dispersion
Polymer type	Acrylic based
Minimum film formation temperature	7 – 12 °C
% Solids	45 – 55%
Appearance	Milky white, creamy, free from lumps
Ultraviolet Resistance	Good
Alkali Resistance	Good

The colors of hardened GFRC products are generally close to the color of the binder used. White colored products can be obtained by using white Portland cement. It is more preferable to add powder and/or water-based pigments to the mixture in the production stage instead of painting later when colored products are desired. It is not always possible to obtain the pigment color added in the mixture at hardened GFRC product. Therefore, in order to remain on a scale close

to the desired color, many trial mixes should be made, and the production process should be kept under good control. Extremely dark exterior finishes should be avoided as this will increase the heat from the sun. The externally used GFRC elements such as coatings may be subjected to excessive thermal expansion and movement on the boundaries of the fixing elements with this heat effect. The combination of the internal stress caused by the temperature difference between the outer surface of a thin element and the inner surface delimited by the thermal motion might cause excessive deterioration and cracking [1].

One of the additives used to improve the properties of the cement-based matrix in GFRC is the micro fillers. Due to the growth of portlandite crystals, defects might develop on the fiber surfaces. These defects occur due to deformations in the GFRC. These deteriorations can be reduced by the pozzolanic reactions of micro-fillers.

Microsilica is highly reactive with calcium hydroxide in the cement matrix. The benefits of reactivities of very small particles ($<1\ \mu$m) are currently being utilized in concrete technology. Microsilica improves the durability of GFRC by improving its strength and increase its density [1]. However, microsilica does not contribute much to increase the tensile and flexural strength of GFRC [3].

Bartos J.M. and Zhu W. [41], have reported that microsilica prevents crystallization of $CaCO_3$ between the filaments of a wire and the fracture continues in telescopic mode for a long time as desired. In addition, Bartos J.M. [1] stated that the addition of microsilica makes the production of GFRC and technical demand for pre-impregnation of the glass fiber strands difficult. Therefore, the use of microsilica in GFRC technology is limited and is generally not preferred.

2.2.6 Water

It should be ensured that the water used in the production of GFRC is free of harmful substances and clean. Water should be carefully selected in accordance with normal concrete technology standards. Drinking water is suitable for these norms [23], [42]

2.3 Manufacture of GFRC

Different methods are used for different purposes in the manufacture of GFRC. In this section, manufacturing designs and manufacturing methods are explained in detail.

2.3.1 Casting and Mixing

Due to definition, GFRC being a composite material consisting of Portland cement, aggregate and water presents a wide range of mixtures. A wide variety of products can be obtained by using different mixture components, ratios and methods. Thus, the mechanical and physical properties of the GFRC product can be determined by the method of production, mixing ratio, fiber type, etc.

GFRC products are usually produced in thin sections such as 10 to 15mm. The materials forming the GFRC are carefully weighed with low-volume additives that require precision. The solids are weighed up to ±2% in accordance with the targeted amount. Liquid materials are usually measured at the same precision by weight or volume [1].

In the spraying method, it is usually possible to produce GFRC up to 125kg. With modern GFRC mixers, it is possible to produce this scale in less than 5 minutes. The mixers used for this method produce slurry for the production of sputtering with high speed cutting tools. In the second stage, it allows the pre-cut glass fibers to be mixed into the cement paste by turning at low speed for premix production [1]. It is sufficient to mix a mixture for 60 to 120 seconds to prepare for production. The amount of glass fiber in the spraying method is generally dependent on the spray cutting speed of the spray device and the spraying pressure of the cement mortar. For this reason, in order to determine the amount of glass fiber, controls should be made in accordance with the standard EN 1170-3 [43].

Compared to the spray method, the mixing capacity can be up to 250 kg in the premix method. However, considering the decrease in workability over time, the

amount of the mixture should be determined correctly. Specially designed mixers are used for GFRC, where materials are usually loaded into the mixer in a large scale production [1]

Although there are separate systems for mixing and spraying for the spray method, the highest efficiency and quality are achieved in integrated spraying systems.

2.3.2 Production of GFRC elements

The microstructural characteristics and performance of the hardened GFRC depend on the manufacturing process. In order to obtain a good performance, compaction must be done very well in the production stage.

In the spraying method, the compaction is achieved by the compression of the materials with the spraying device. In addition, it is ensured that the material is compacted by applying compression to each layer by special tools such as rollers.

In the premixed production, compaction is achieved by hand or with the help of a trowel and subjecting the mold to vibration [1].

In addition, if an additive for self-compaction is used in the mixture, the need for compaction is eliminated.

The production method also determines the orientation of the fibers and the degree of anisotropy of GFRC [1]. The majority of the fibers in the spraying are parallel to the die surface and in the longitudinal direction of the plate. The two-dimensional distribution of the fibers parallel to the plate plane increases the bending strength.

2.3.2.1 Premix method

In the premix method, cement-based matrix is first produced and pre-cut alkaline-resistant glass fiber is added to the mixture in the second step.

In the premix method, it is difficult to ensure proper distribution of fibers in the matrix and a higher w/b ratio is required compared to the spraying method. To

achieve uniform dispersion of the fibers, increasing the intensity of the mixture causes damage to the fibers and the separation of the strands into smaller pieces. This result in a product with lower workability and lower performance than the spray method. Which is because of the high w/b ratio and the 3D distribution of the fibers. Special mixers and mixing methods have been developed to overcome such difficulties [5].

After the addition of the fibers to the mixture, the casting is done by hand or by a pumping system and the mold is exposed to vibration. If an admixture is used to provide self-compacting, it can be cast without the need of vibration. In addition, the fresh premix mixture can also be produced using a special spray gun without the need for external compression. The spray gun used in this case is different from the simultaneous spraying method.

2.3.2.2 Simultaneous spray up method

In the spraying method, the GFRC mixture is cast directly to the mold with a special spray gun. The spray gun has two units for processing fibers and mortar. The first serves as a glass fiber chopper fed to the spray gun. The latter simultaneously injects the freshly made cement-based matrix into the spray nozzle to atomize and mix it with chopped wires. The glass fiber cement-based matrix obtained from these processes is sprayed from the spray head to the mold surface. In the spraying method, GFRC is generally produced with higher fiber contents up to 5% [1].

In the spraying method, a thin mist layer is first sprayed. Then the glass fiber layer is sprayed. Compacting is carried out with a roller after the 4-6 mm thick layers sprayed by the spray gun at each pass. In the spraying process, production should be done by paying attention to the homogeneity of the mold edges. After spraying the last layer, a hand roller is clamped, and the rear face is prepared with the help of a float. Thickness measurements should be made and finished according to production requirements.

2.3.3 Curing

The length of the curing time and the curing conditions significantly affect the properties of hardened GFRC. It is aimed to prevent loss of water and to maintain the freshly made product at sufficient temperature as in ordinary concrete technology. However, since the amount of cement in GFRC is higher than the ordinary concrete, curing should be controlled more accurately. It is important to keep the internal moisture and to prevent losses by evaporation from the fresh composite during its curing time. Curing environment can be obtained by adding a small amount of acrylic polymer.

Different curing methods are applied for productions with and without acrylic polymers. GFRC containing acrylic polymers should be covered overnight and dry cured after removal from the mold. The temperature should be between 5 and 35°C for 2 days after production. [40].

In production without acrylic polymer, GFRC should be cured at controlled temperature and humidity. Ideally, it is 20 °C and 95% relative humidity (RH) for 7 days [40].

2.3.4 Moulds and Formwork

GFRC is an ideal material for productions of complex shapes. High-quality molds are produced for this purpose. Molds produced for complex shapes of GFRC can be reused more often than the ordinary concrete. Therefore, high-quality molds for GFRC production provide better performance than ordinary concrete technology. On the other hand, GFRC is produced in thin thickness compared to ordinary concrete, so the material weight is much lower. Therefore, molds can be produced in much larger sizes and complex shapes.

The molds used in GFRC should be within the limits to meet the dimensional changes of the material. The mold material selection depends on panel shape, required mold hardness, water resistance, and cost. In the early years of GFRC, rigid molds were produced from plywood or steel. Subsequently, fiberglass molds

have been shown to be more suitable for producing complex shapes. The current GFRC productions use molds made of two composite materials, in which a rigid base is lined with another material, such as steel lined with polyurethane rubber are widely used [1].

Molds filled with fresh GFRC should be stored at 5 to 40°C and molds should be stored on a flat surface, supported in such a way that mold will not bow or twist [40].

2.3.5 Surface Finishes and Treatments

Surface finish is important because GFRC products are often used as exterior coating products. Surface finishes should be made in a way that does not allow crack formation. These cracks then deteriorate the aesthetic appearance by accumulating dust. Fine aggregates provide ease of surface finish in GFRC. Thus, surface finishes can be made in different shapes easily using various shaped molds.

The surface of the mould reflects the initial surface finish of the GFRC. Therefore, there should be no defects or visible joints on the mold surfaces. The original surface of the GFRC is then treated to obtain various surface finishes. Smooth and polished molds or mold liners produce equally smooth, even glossy GFRC surfaces. In addition to appropriately shaped molds, sometimes textures and patterns formed by spraying or pouring onto liners, the surfaces of the GFRC can also be chemically or mechanically processed when the product is freshly extruded or cured [1].

2.3.6 Handling, Transport, and Storage

GFRC products are particularly manufactured in thin thickness, therefore they should be handled, transported and stored properly. Special lifting frames are used for the transport of large panels and the lifting points specified in the design must be used. The embedded fixings can be used for lifting as long as they are suitable for handling. However, due to their thin construction, they must be

securely fastened during transportation, as vibration and movement of the material may cause damage. Additional protection must be provided for sensitive spots such as corners and edges. Improper storage may lead to damage and unacceptable deformations. Therefore, the temperature and humidity of the storage environment should be kept at appropriate values and GFRC should be protected from any environmental effects [1].

2.3.7 Cutting and Shaping

Hardened GFRC can be cut and shaped with diamond-tipped saws and drills used in conventional concrete technology. In addition, as a result of the latest developments with the laser beam, precision cuts can be made with the least amount of waste [1].

2.4 Fracture Mechanism

The fracture mode following the initial cracking of the matrix varies with the properties of the matrix and the fiber as well as the bond between them. Furthermore, the fracture mode is also significantly associated with the bond between the individual filaments within the strand. Ageing of the GFRC and the conditions of exposure affect the bond between the matrix and the fiber and the filaments within a strand. Three types of failure mechanisms occur at the limit of proportionality (LOP) following the first crack in the matrix. At this stage, the tensile strength of the matrix is overcome by the internal stress that is formed by the load and the matrix cracks. The load taken by the matrix is added to the fibers crossing the crack that is already carrying the load. The load carrying capacity of these fibers varies according to many factors such as length, angle with respect to the direction of stress, and internal bond. The increase in load causes the failure of the strands and collapse. This fracture mechanism occurs in 3 different types [1].

The First mechanism takes place by the complete pullout of the strands when the bond between the fiber and the matrix is low. Although the bond between the matrix and the fibers is weak, the bond between the fibers within a strand is strong. Thus, the strand itself acts as a single reinforcement. In this mechanism, the majority of the strands are pulled out instead of breaking in tension. A similar effect can be observed where the length of the strand is short [1].

The second mechanism is a 'telescopic' or 'combined' failure mode where the bond between the matrix and the peripheral fibers of the strand is strong. In this mode, the peripheral fibers of the strand take up the majority of the additional load transferred from the matrix and eventually fail in tension. After this point, the tension is transferred to the inner fibers of the strand. The inner fibers then gradually carry the load until all the fibers are broken. In this mechanism, the friction between the fibers allows them to continue with some internal stress transfer [1].

The third mechanism is the complete tensile fracture of the strand in which the bond between the fibers in the strand and the bond between the strand and the matrix is strong. The strand then acts as a single reinforcing element as in mode 1 and fails in a complete tensile fracture with minimum or no pull out at all. In this mode, although the strength of the composite is enhanced, it shows a brittle fracture with a sudden failure[1].

Although the fracture modes take place in 3 modes as mentioned above, any fracture mode can occur at any age.

3
Experimental Studies

3.1 Materials

The materials used in the production of GFRC mixes are white Portland cement, fly ash, blast furnace slag, silica sand, acrylic polymer and superplasticizer. ÇİMSA super white Portland cement (CEM I 52.5 R) was used as the cement. It is a highly reactive binder with an early age strength among other cement types. Type F fly ash used in the study was obtained from the Çatalağzı thermal power plant and the ground granulated blast furnace slag was obtained from Bolu Cement Company. Chemical composition and physical properties of the binders used in the experimental study are presented in Table 3.1. A commercially available acrylic polymer was used as an additive in half of the mixes. Melamine based superplasticizer was used at varying dosages to achieve a workable matrix. Alkali resistant glass fiber (AR-glass fiber) manufactured by Nippon Electric glass was used as the fiber. Density, tensile strength, young's modulus and strain to failure of glass fiber is reported to be 2800 kg/m^3, 1500 N/mm^2, 74000 N/mm^2 and 2% respectively according to the manufacturer. In the reference mixtures, only cement was used as the binder. The fly ash and blast furnace slag substituted the cement by 50% by mass. In the mixtures in which both pozzolanic materials are used together, the cement is equally substituted with fly ash and slag. The mixtures were coded according to the first letter of the constituent materials as C, F, S, P and G letters which represents cement, fly ash, slag, polymer, and glass fiber respectively. The number following the letter "C", "F", "S" refers to the percent mass of the cement, fly ash and slag in the binder. The numbers following the letter "G" refers to the percent of the glass fiber. 'P' was used where polymer was incorporated in the mix by 5% by mass of the total binder.

Table 3.1 Chemical composition and physical properties of the binders

Oxide % by mass	Cement	Fly ash	Blast furnace slag
SiO_2	21.6	52.6	40.6
Fe_2O_3	0.3	5.8	1.2
Al_2O_3	4.1	25.0	12.6
CaO	65.7	3.3	35.1
MgO	1.3	2.1	5.8
SO_3	3.3	1.0	0.1
Na_2O	0.3	0.3	0.8
K_2O	0.3	4.1	07
Specific Weight, g/cm^3	3.06	2.21	2.91

The particle size distribution of cement, fly ash, slag and fine aggregate used in this study was determined by Malvern Mastersizer 2000 instrument. The mean particle size of cement, fly ash, slag, and sand were determined as 15.45 μm, 23.19μm, 10.43μm and 561 μm respectively, and the particle size distribution of the solid materials are shown in Fig. 3.1. In addition, particle shape of the materials was visualized through SEM images. The particle shapes of the Portland cement and blast furnace slag is rough and angular as shown in Fig. 3.2. On the other hand, the particle shape of the fly ash is spherical with a high degree of smoothness. The particle shape of the silica sand is rough and angular.

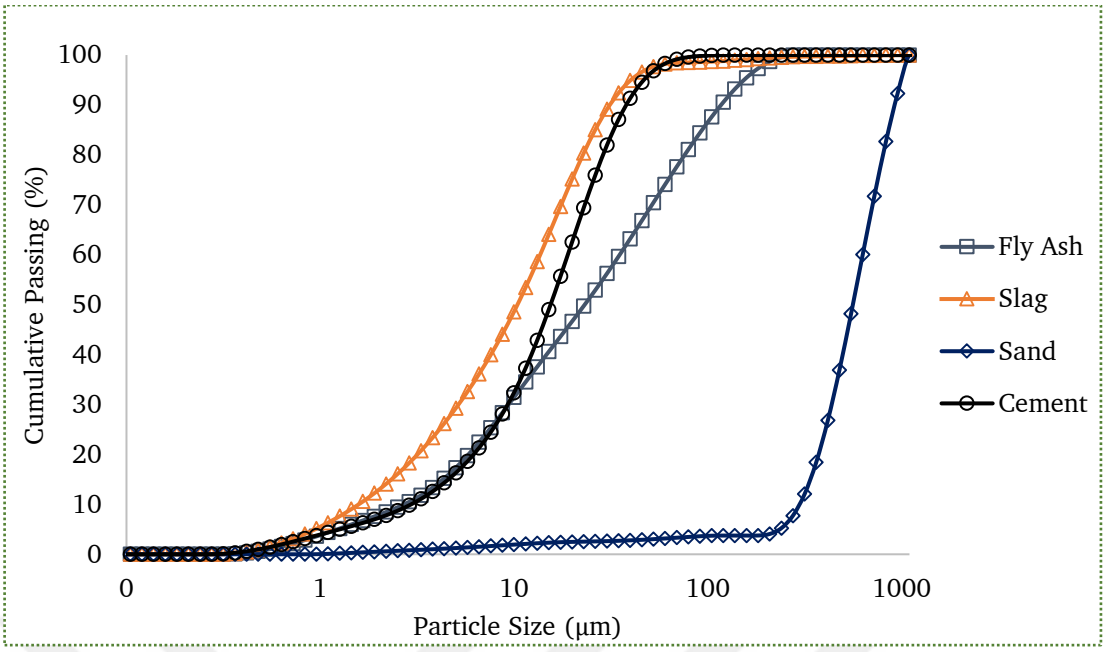


Figure 3.1 Particle size distribution of solid materials

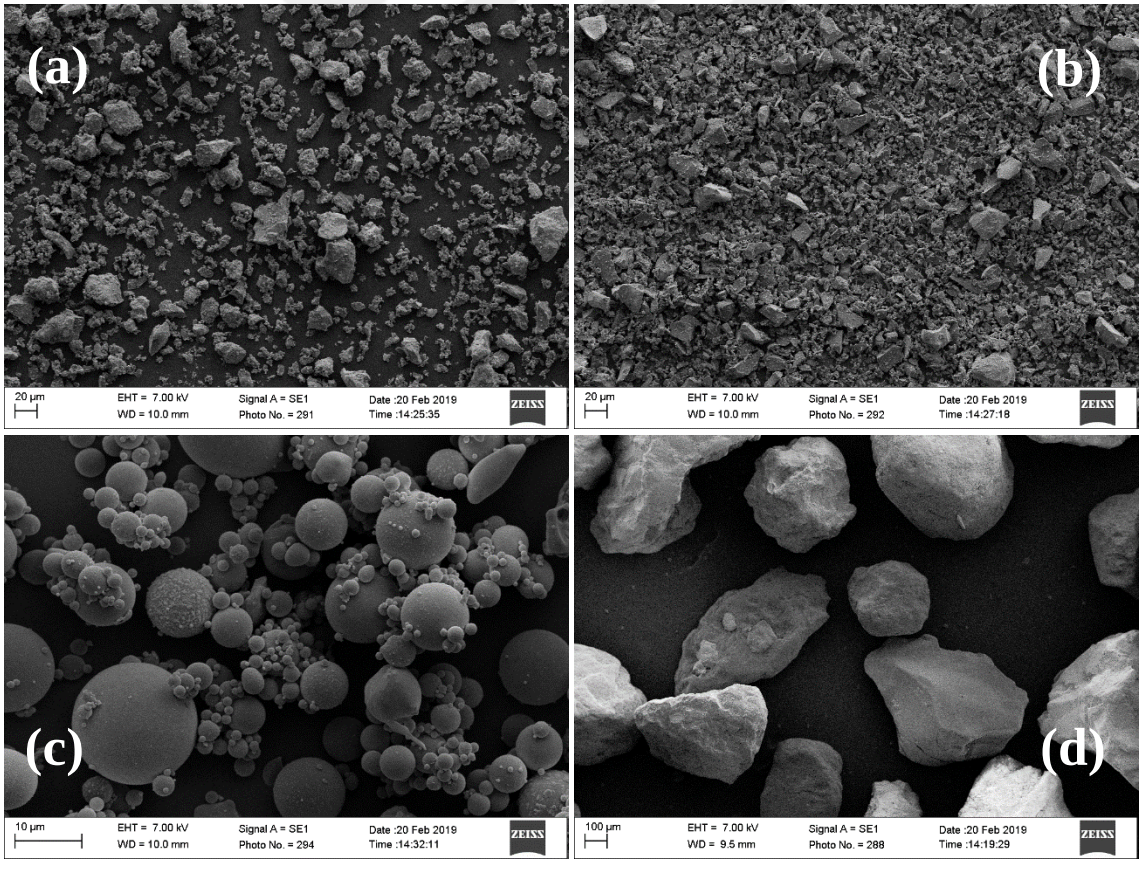


Figure 3.2 SEM micrographs of (a) Portland cement, (b) blast furnace slag, (c) fly ash, and (d) silica sand

3.2 Production Stage and Mix Design

All productions were made in collaboration with 3H Precast Company. Spraying method was chosen for the production of GFRC mixes. Water to binder ratio and aggregate to binder ratio was fixed as 0.34 and 1.0, respectively in all mixtures. Glass fiber was used in two different ratios as 3% and 4% and polymer ratio was 0% and 5%. The cement substitution ratio was kept as 50% by mass and fly ash was used as cement substitute material. In some mixtures fly ash and blast furnace slag were used together and in equal amounts as cement replacing material. A total of twelve mixtures were prepared and mix proportions are shown in Table 3.2. Each production started by weighing the materials. Initially, water, polymer and superplasticizer were poured into the mixer and mixer was operated. Cement, sand and pozzolanic materials were then added slowly. Mixing continued about 150 s. Following the mixing process the fresh mortar was transferred to the spraying device. Before starting spraying, the glass fiber roll is attached to the device and the spray pressure is adjusted according to the desired glass fiber-slurry ratio. Fresh mortar and glass fiber were then simultaneously sprayed on the panel moulds as shown in Fig. 3.3a. The spray casting continued as multilayers and after the completion of each layer, roller compacting is performed as shown in Fig. 3.3b. After spraying the final layer, the entire surface of the plate was flattened with a trowel to obtain homogenous thickness.



Figure 3.3 (a) Spray casting and (b) roller compacting of the GFRC layers

Table 3.2 Mix proportions

Mix ID	Cement (kg)	Fly ash (kg)	Slag (kg)	Sand (kg)	Super Plasticizer (kg)	Polymer (kg)	Water (kg)	Glass fiber (%)
C100G3	1.0	-	-	1.0	0.0154	-	0.34	3
C100PG3	1.0	-	-	1.0	0.0121	0.05	0.34	3
F50G3	0.5	0.5	-	1.0	0.007	-	0.34	3
F50PG3	0.5	0.5	-	1.0	-	0.05	0.34	3
F25S25G3	0.5	0.25	0.25	1.0	0.0121	-	0.34	3
F25S25PG3	0.5	0.25	0.25	1.0	-	0.05	0.34	3
C100G4	1.0	-	-	1.0	0.0154	-	0.34	4
C100PG4	1.0	-	-	1.0	0.0121	0.05	0.34	4
F50G4	0.5	0.5	-	1.0	0.007	-	0.34	4
F50PG4	0.5	0.5	-	1.0	-	0.05	0.34	4
F25S25G4	0.5	0.25	0.25	1.0	0.0121	-	0.34	4
F25S25PG4	0.5	0.25	0.25	1.0	-	0.05	0.34	4

3.3 Fresh Properties

Workability of GFRC is measured by slump test on freshly mixed slurry prior to addition of glass fibers. Measurements are made according to EN 1170-1 [44]. For this purpose, a plastic tube is used with a smooth surface of 57±0.5 mm internal diameter and a flat plate with dimensions of 300×300 mm. Plate was initially put on a flat surface and inside of the tube and the plate is wiped with a damp cloth. Tube is then placed on the plate and filled with matrix. Surface of the matrix is leveled with a trowel and the tube is subsequently lifted slowly and vertically. The spreading diameter of the matrix is measured with a caliper as shown in Fig. 3.4.



Figure 3.4 Slump Test

3.4 Curing and Test Scheme

Fresh mortar and fiber were simultaneously sprayed on the flat molds with nominal thickness of 20 mm in multilayers and each layer was compacted with a roller and trowel for better compaction and reducing air entrapment. After 24 hours, the sample panel was removed from the mold and stored until the age of 6 days. The schematic representation of the test program is illustrated in Fig. 3.5.

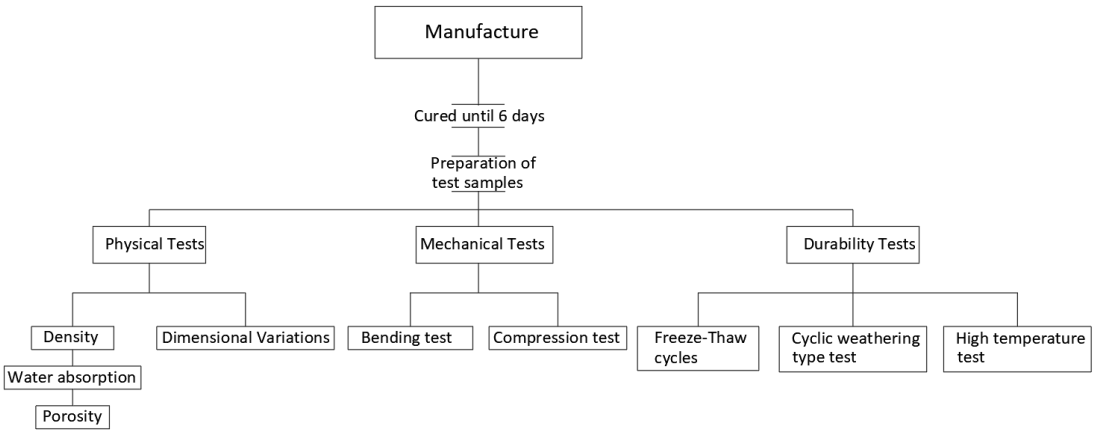


Figure 3.5 Test program

3.5 Physical Properties

3.5.1 Density, Water absorption and Porosity

The density and water absorption of GFRC mixtures is determined according to EN 1170-6 [45]. The dimensions of each sample were measured by rounding to the nearest mm and the volume (cm^3) of each sample was calculated. 4 test pieces were placed in water at 20±2 °C until desired period of time. After removal from water. The test pieces were wiped with a damp cloth to remove surface water. Each test piece was weighed to find the mass after immersion and then stored in a ventilated drying oven until they reach constant mass of "m_d" approximately for 24 hours as shown in Fig 3.6. Density (γ), water absorption (ρ_d), and porosity (p) were determined by using equations (3.1), (3.2) and (3.3).

$$\gamma = \frac{m_w - m_d}{m_d} \times 100 \tag{3.1}$$

$$\rho_d = \frac{m_d}{V} \tag{3.2}$$

$$p = \frac{m_w - m_d}{V} \times 100 \tag{3.3}$$



Figure 3.6 Weighing (left) and placing (right) the test pieces in the ventilated drying oven

3.5.2 Dimensional Variations Test

The dimensional stability of the GFRC mixtures is tested in accordance with EN 1170-7 [46] on 6 samples with dimensions of 50×325 mm. Samples were stored in the laboratory at a temperature of 20±3 ºC and 60±5 % RH until they reached 10 days of age. The test began with the measurement of the initial lengths (l_0) of the samples. 3 samples from each mix were placed in the ventilated drying oven with a temperature of 33±3 ºC for 21 days for shrinkage test as shown in Fig 3.7a. The samples were removed from the oven to measure the final length (l_2) as shown in Fig 3.8 and the shrinkage value was calculated by Equation (3.4). The other 3 samples were immersed in water with a temperature of 20±2 ºC for 96 hours for the expansion test as shown in Fig 3.7b.



Figure 3.7 (a) Placing the test pieces in the ventilated drying oven and (b) immerison in the water

Samples removed from the water was wiped with a damp cloth, final length (l_1) was measured as shown in Fig. 3.8 and the expansion value was calculated by Equation (3.5). The value of extreme dimensional variation was finally determined by using Equation (3.6), as the sum of the shrinkage and the expansion values.

$$\frac{\Delta l_s}{l} = \frac{l_0 - l_2}{l_0} \times 10^3 \quad (3.4)$$

$$\frac{\Delta l_e}{l} = \frac{l_1 - l_0}{l_0} \times 10^3 \quad (3.5)$$

$$\frac{\Delta l_c}{l} = \frac{\Delta l_s + \Delta l_e}{l} \times 10^3 \quad (3.6)$$



Figure 3.8 Measurement of parameters for shrinkage and expansion

3.6 Mechanical Properties

3.6.1 Matrix Properties

In order to determine the compressive and flexural strength of the matrix phase, samples with dimensions of 50×50×50mm and 20×50×325mm were produced, respectively. Tests were performed at 7, 28 and 90 days to determine the compressive and flexural strength development and also for comparison of the matrix properties of different mix formulations. Compressive strength of samples was calculated by simply dividing the failure load by the area of the samples. Flexural strength is determined by using the following equation (3.7):

$$f_f = \frac{P \times L}{b \times d^2} \tag{3.7}$$

where f_f (MPa) is the flexural strength, P (N) is the failure load, b (mm) is the width and d (mm) is the thickness of the sample.

3.6.2 Flexural/Bending Strength

The strength of concrete is one of the most important parameters for designing a safe structure. Bending strength is a key feature giving fundamental information about the strength of the structure. In this study, in order to determine the flexural properties of GFRC, 4 point bending test was carried out according to EN 1170-5 [47] on samples with nominal dimensions of 20×50×325mm. Test was performed at 7, 28 and 90 days to determine the strength development of GFRC mixtures. Samples were kept in water for 24h before the test date. Schematic diagram of the storage phase for bending test is shown in Fig. 3.9. After removed from the water, samples were wiped with a damp cloth, they were placed on the two-bottom support with a span of L=300mm between them and two supports were placed on top surface of the samples with a span of 100mm as shown in Fig 3.10.

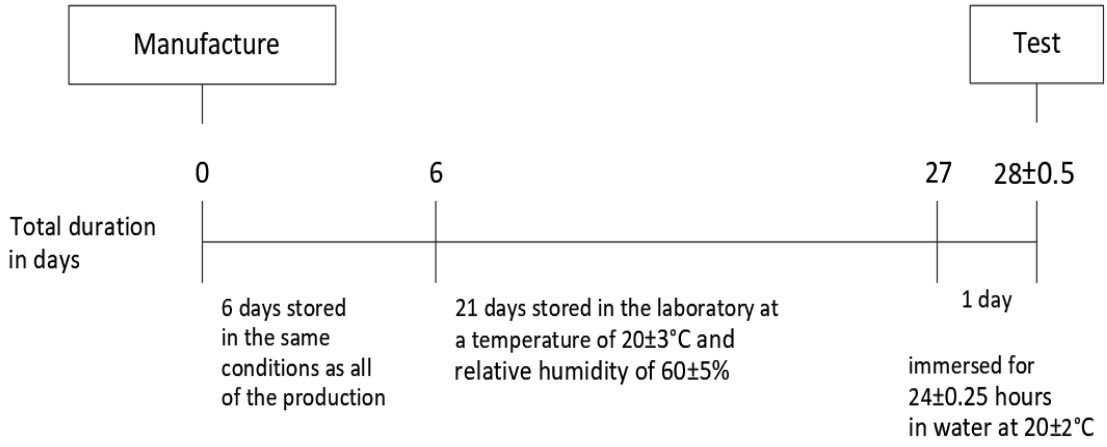


Figure 3.9 Schematic diagram showing the storage phases of the GFRC

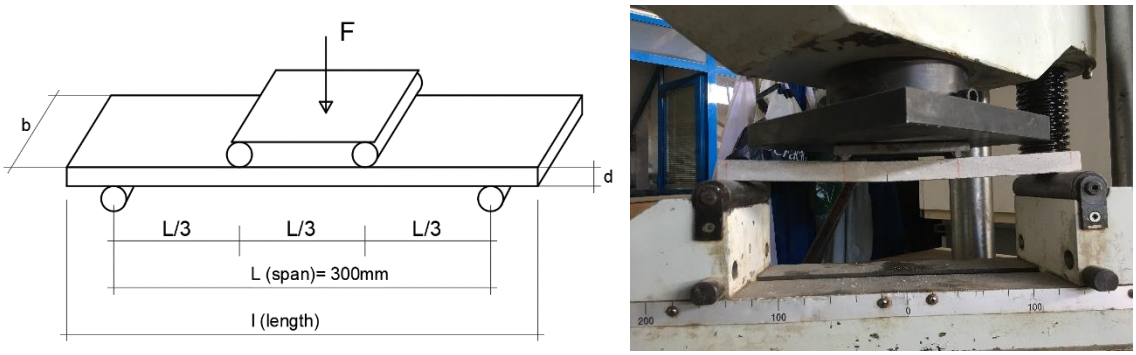


Figure 3.10 Representation of flexural test

The bending test continued until the fracture of the samples. Loading process was tracked by a computer linked to the test machine. Load and deflection values was recorded throughout the test. Subsequent to bending test, width and thickness in the vicinity of the cracking point was measured and recorded. The deformation (ε_{LOP} and ε_{MOR}) and stress (σ_{LOP} and σ_{MOR}) values were calculated using the equations (3.8), (3.9), (3.10) and (3.11).

$$\varepsilon_{LOP} = \frac{108}{23} \times \frac{\Delta_{LOP} \times d}{L^2} \tag{3.8}$$

$$\varepsilon_{MOR} = \frac{108}{23} \times \frac{\Delta_{MOR} \times d}{L^2} \tag{3.9}$$

$$\sigma_{LOP} = \frac{F_{LOP} \times L}{b \times d^2} \tag{3.10}$$

$$\sigma_{MOR} = \frac{F_{MOR} \times L}{b \times d^2} \tag{3.11}$$

3.7 Fracture Toughness

The toughness of the GFRC mixes was calculated by the area under the load-deflection curves up to the point where the post-peak load reaches 75% of the maximum load as shown in Fig 3.11.

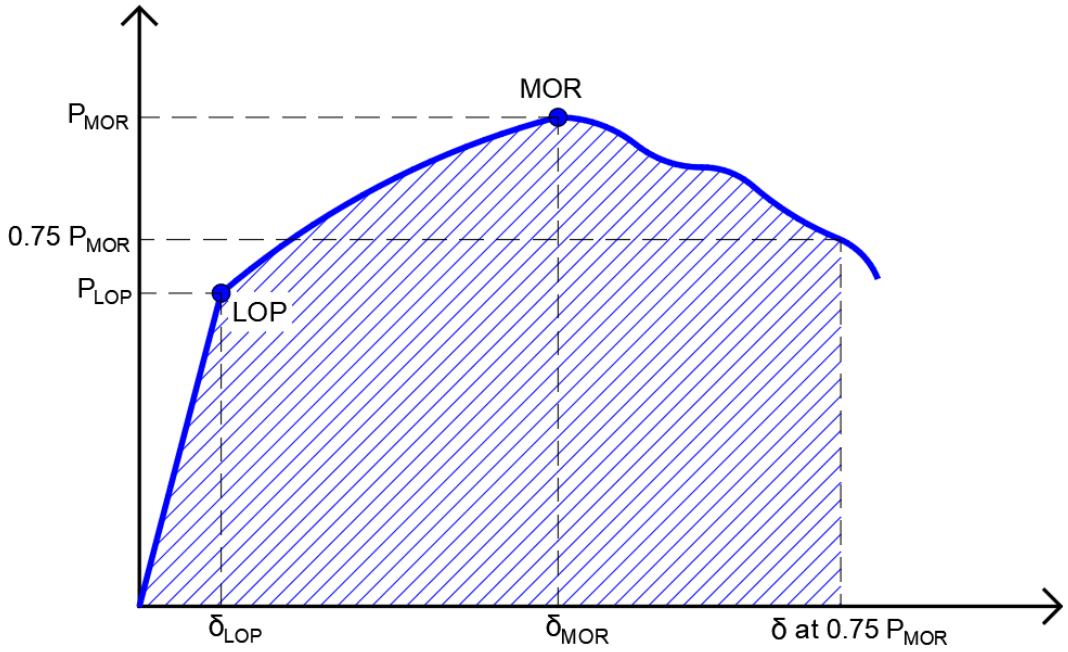


Figure 3.11 Calculation of toughness

3.8 Durability Properties

Durability of GFRC mixtures were determined by exposing the samples to freeze/thaw cycles, wet/dry cycles and to elevated temperatures of 600 and 800°C. The performance of the mixtures was evaluated by conducting bending test and determining the residual strength after each effect. Details of the test procedures are presented in the following sections.

3.8.1 Freeze/Thaw Cycles

Changes in the mechanical properties of GFRC material due to cold weather conditions are examined through this experiment. The test was carried out in accordance with EN 13198 [48] when the test specimens reached 28 days of age. The samples were kept in water for 3 days at temperature of (20±5) ºC prior to testing, therefore it was ensured that the test specimens were in saturated conditions when the test started.

The test consisted of two phases; freezing phase in a freezing cabinet and a thawing phase in water. Freeze/thaw cycles began with freezing phase at -20±5 ºC temperature for 1h 15 min±5 min and proceeded with the thawing phase at 20±5 ºC temperature for 1h in a tank filled with water. Detailed diagram of a freeze-thaw cycle for the GFRC mixes is shown in Fig. 3.12. The standard procedure requires 25 cycles. By the end of the freeze/thaw cycles, bending test was performed in accordance with EN 1170-5 [47] to observe the changes in mechanical properties of GFRC. Schematic diagram of the storage phase of the freeze-thaw test is shown in Fig. 3.13.

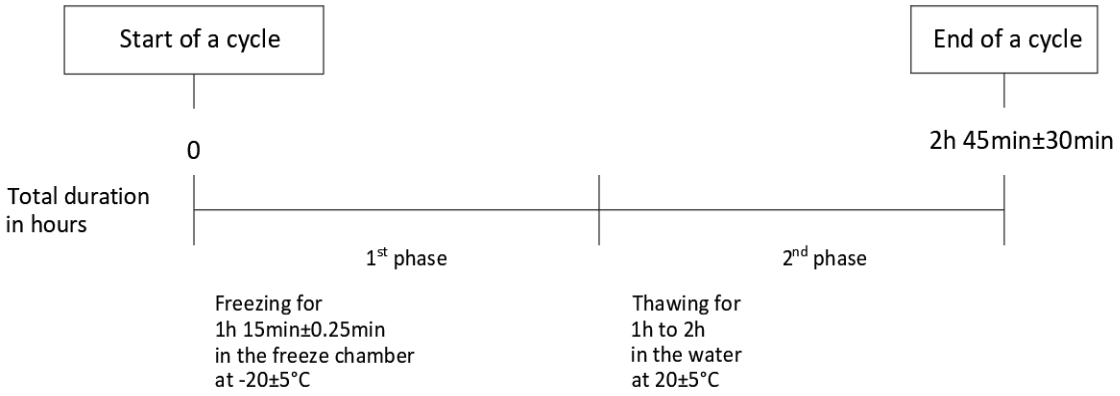


Figure 3.12 Detailed diagram of a freeze-thaw cycle for the GFRC mixes

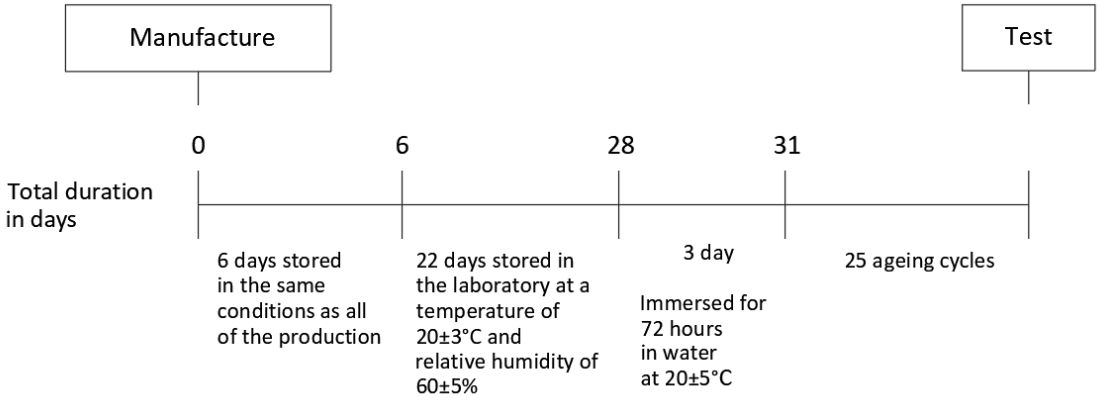


Figure 3.13 Schematic diagram of the storage phases of the GFRC mixes exposed freeze-thaw cycles

3.8.2 Cyclic Weathering Test

The effects of environmental factors such as water and temperature on the mechanical characteristics of GFRC was scrutinized through this test. This test was carried out according to EN 1170-8 [49]. The test consists of 4 phases: immersion in water, drying, exposure to hot air and cooling. The test started by immersing the samples in water for 24±0.25 h at a temperature of 20±2 ºC. In the second phase samples are exposed to drying at a temperature of 70±5 ºC for 30±5 min in the ventilated drying oven. The samples were then exposed to hot air at a temperature of 70±5 ºC for 23±0.25 h in ventilated drying oven. Finally, a cycle is completed by cooling the samples at a temperature of 20±2 ºC for 30±5 min. Detailed diagram of cyclic weathering test is shown in Fig. 3.14. Samples were subjected to 50 cycles in accordance with the standard. In order to investigate the effect of wet-dry cycles on the mechanical properties, 4 point bending test was performed in accordance with EN 1170-5 [47] at the end of the cycles. Schematic diagram of the ageing phases of the GFRC mixes exposed to wet-dry cycles is shown in Figs. 3.15.

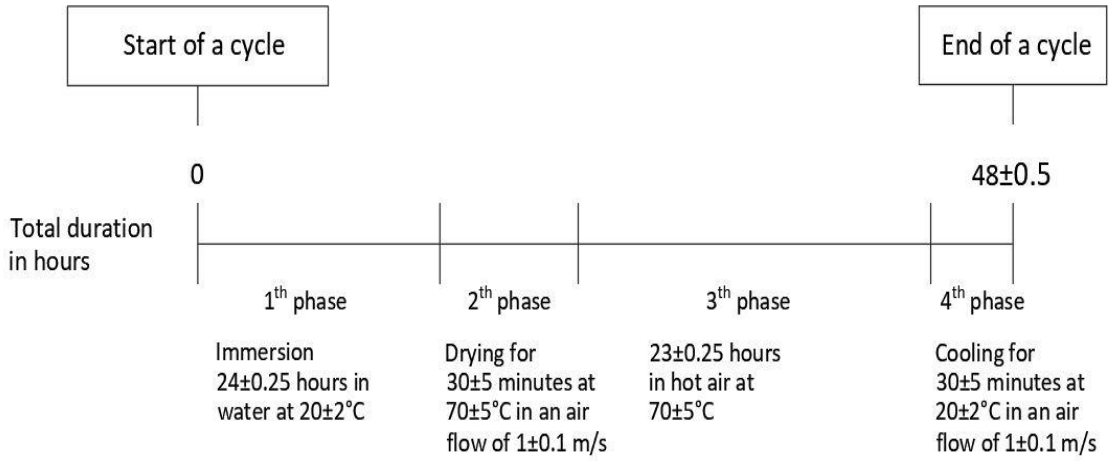


Figure 3.14 Detailed diagram of a wet-dry cycle for the GFRC mixes [49]

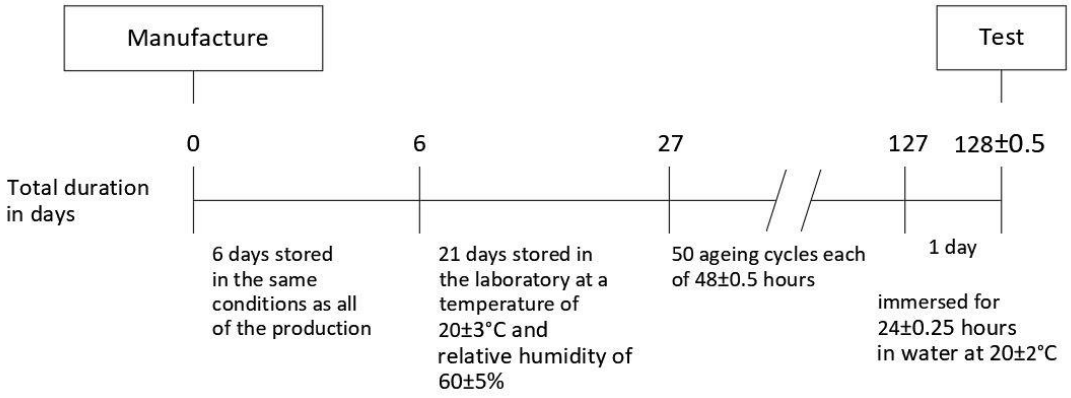


Figure 3.15 Schematic diagram of the storage phases of the GFRC mixes exposed 50 wet-dry cycles [49]

3.8.3 High Temperature

This test was carried out to investigate the changes in the mechanical and physical properties of the GFRC mixes exposed to high temperature effect. The samples were exposed to temperatures of 600 °C and 800 °C and kept at these temperatures for 2 hours. After cooling the samples to room temperature, bending test was performed in accordance with EN 1170-5 [47] standard to investigate changes in the mechanical properties. In addition, the samples were photographed under microscope to observe the surface cracks that formed as a result of the high temperature effect.

3.9 Microstructure

The microstructure of the GFRC mixes was investigated by Zeiss EVO® LS 10 model Scanning Electron Microscope (SEM). For this purpose, small samples were cut from test pieces belonging to different GFRC mixtures and analyzed under SEM to visualize fiber dispersion in the matrix and collect information about the microstructure.

4
Discussion of Test Results

4.1 Workability

The workability of GFRC mixtures was determined by slump test and the results are plotted in Fig. 4.1. The figure clearly shows that the polymer addition significantly improves the workability of the GFRC mixes. Fly ash consists largely of spherical shape particles and its presence in cement mixtures improves workability due to ball-bearing effect, improves the dispersion of cement particles, and increases packing density of the solid material [50]. However, when fly ash is used in combination with blast furnace slag the workability was not significantly changed compared to the reference mix (C100). The need for superplasticizer was reduced in the mixes where fly ash was incorporated and the need for superplasticizer was completely eliminated in the mixtures with fly ash and polymer as seen in Table 3.2.

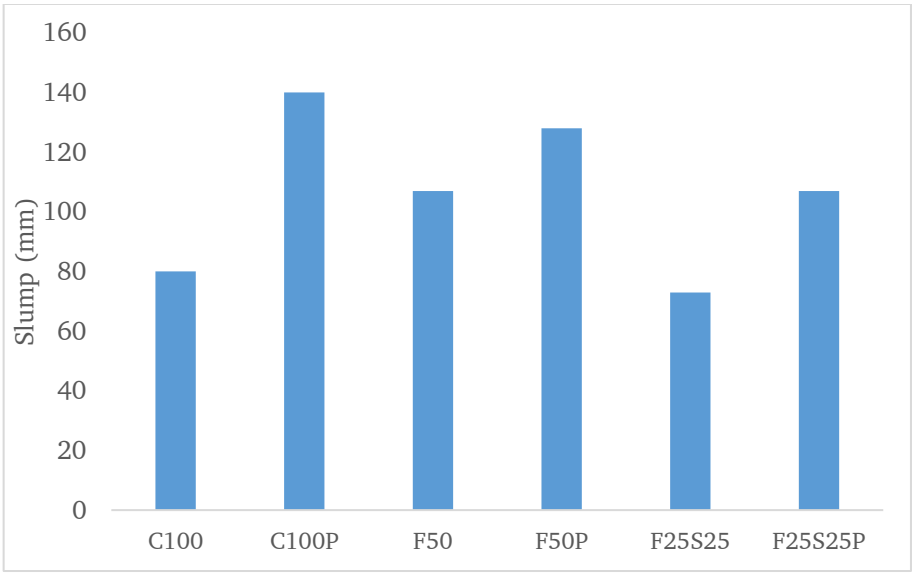


Figure 4.1 Slump Test Results

4.2 Physical Properties

4.2.1 Density, Water Absorption and Porosity

The dry density of GFRC depends primarily on the density of the matrix and the density of the matrix generally depends on the density of the aggregate and the degree of compaction of the fresh mixture. A well compacted GFRC material has a low water permeability as well. Dry density of the GFRC mixes were determined at 7 and 28 days and the average of the results are shown in Table 4.1. Dry density values of the mixtures varied between 1870 and 2018 kg/m^3. The density values of the mixes increased with age due to the filling of the pores by the hydration products. Polymer addition resulted in slight reduction in the density values of the GFRC mixes. Substituting cement with fly ash and slag significantly reduced the dry density.

Table 4.1 Dry density results of the GFRC mixes

	Dry Density (kg/m^3)	
Mixtures	**7 days**	**28 days**
C100G3	1999	2018
C100P5G3	1976	1990
F50G3	1928	1956
F50P5G3	1870	1891
F25S25G3	1932	1962
F25S25P5G3	1909	1944
C100G4	2000	2001
C100P5G4	1941	1968
F50G4	1910	1935
F50P5G4	1871	1922
F25S25G4	1923	1975
F25S25P5G4	1908	1962

Water absorption test results of the GFRC mixes at 7 and 28 days are shown in Figs. 4.2 and 4.3. Test results show that the water absorption of the mixes reduce

by age. Acrylic polymer inclusion provided a slight reduction in the water absorption values. The lowest values were obtained in mixes incorporating fly ash, slag, and polymer due to the pore filling capability of the unreacted particles and reduced capillary pores with pozzolanic reactions. The increase in fiber content, on the other hand, was found to insignificantly affect the water absorption at 7 days, however, 28 days water absorption was significantly reduced in the mixes incorporating pozzolanic materials.

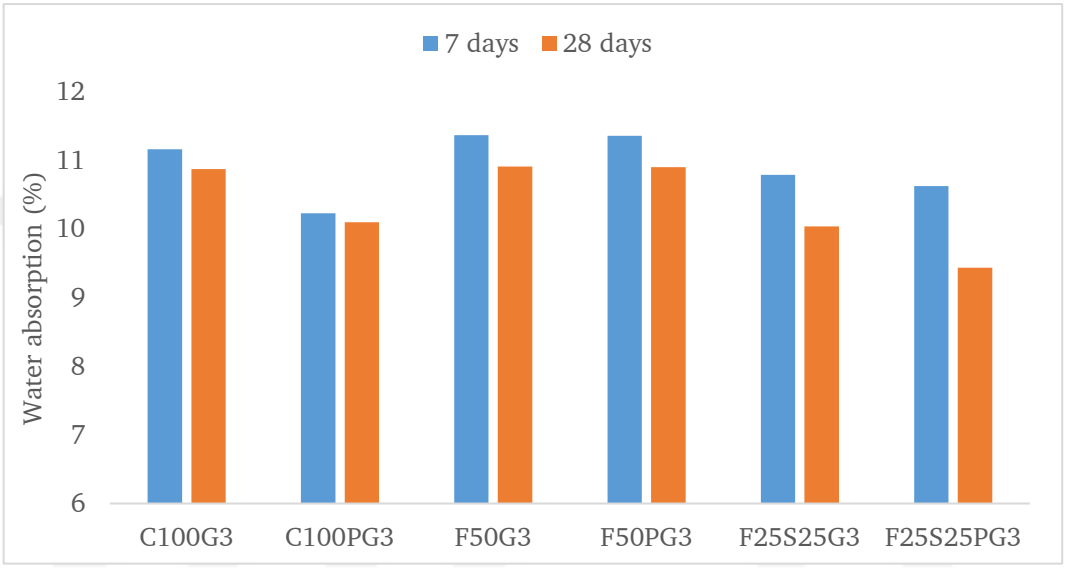


Figure 4.2 Water absorption of GFRC mixes with 3% fiber

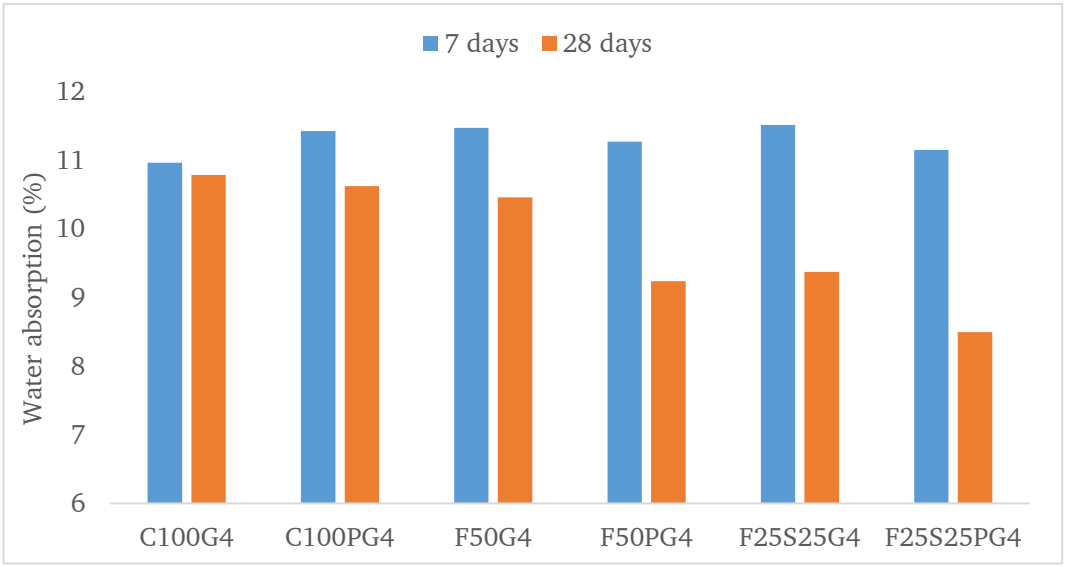


Figure 4.3 Water absorption of GFRC mixes with 4% fiber

The porosity of the mixes varied between 20-22% and 17-22% at 7 and 28 days, respectively as shown in Figs 4.4 and 4.5. The porosity of the mixes incorporating fly ash and slag were found to be significantly reduced at 28 days compared to the reference mixes as in water absorption.

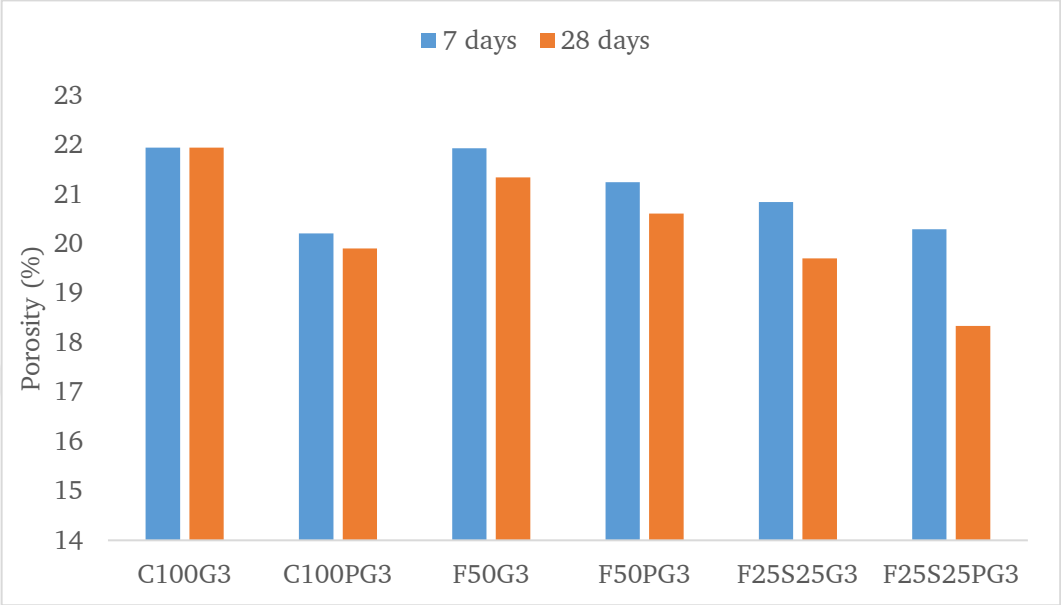


Figure 4.4 The apparent porosity of GFRC mixes with 3% fiber

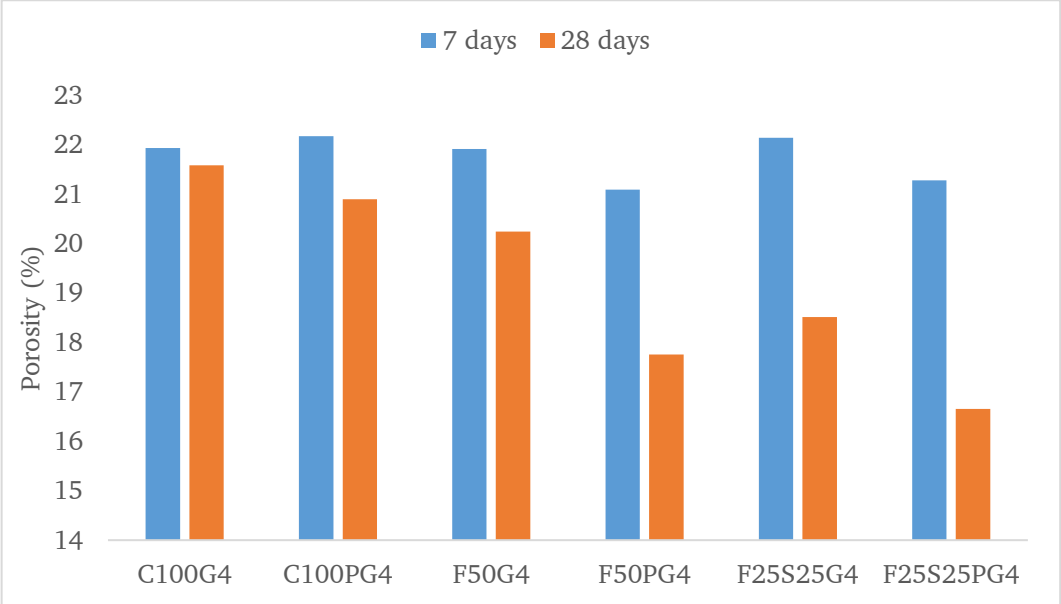


Figure 4.5 The apparent porosity of GFRC mixes with 4% fiber

4.2.2 Dimensional Variations

Dimensional variations are of primary importance during the service life of the GFRC. GFRC is a product that is produced as precast and assembled at the site. The fixing systems must be designed with the consideration of dimensional changes due to humidity and heat during service life with loads. Dimensional variations are expressed as the sum of shrinkage caused by the effect of humidity and expansion caused by temperature effect. All cement-based materials produced with high amounts of OPC are subjected to dimensional variations due to moisture and heat during their service life. Therefore, attempts to reduce the amount of cement decrease the dimensional changes. At the curing stage after production, as the drying occurs, the GFRC material is subjected to shrinkage. As a result of wet curing, the material begins to expand but does not return to its original dimensions. In subsequent service conditions, irreversible shrinkage occurs due to the moisture content of the cement. Fig 4.6 shows the expansion and shrinkage values and Fig. 4.7 shows the extreme dimensional variations of GFRC mixtures depending on the shrinkage and expansion. Test results showed that the shrinkage values were significantly higher than the expansion values. Shrinkage and expansion of GFRC mixes were reduced by replacing cement with fly ash and slag. Extreme dimensional variations (sum of shrinkage and expansion) of the mixes containing fly ash is reduced by more than 25% compared to the reference mixtures. On the other hand, the addition of blast furnace slag increased the dimensional changes, but the value still remains below the reference mixes. Although the addition of acrylic polymer reduced the dimensional changes in the reference mixtures, the same trend was not observed in mixes with fly ash and slag.

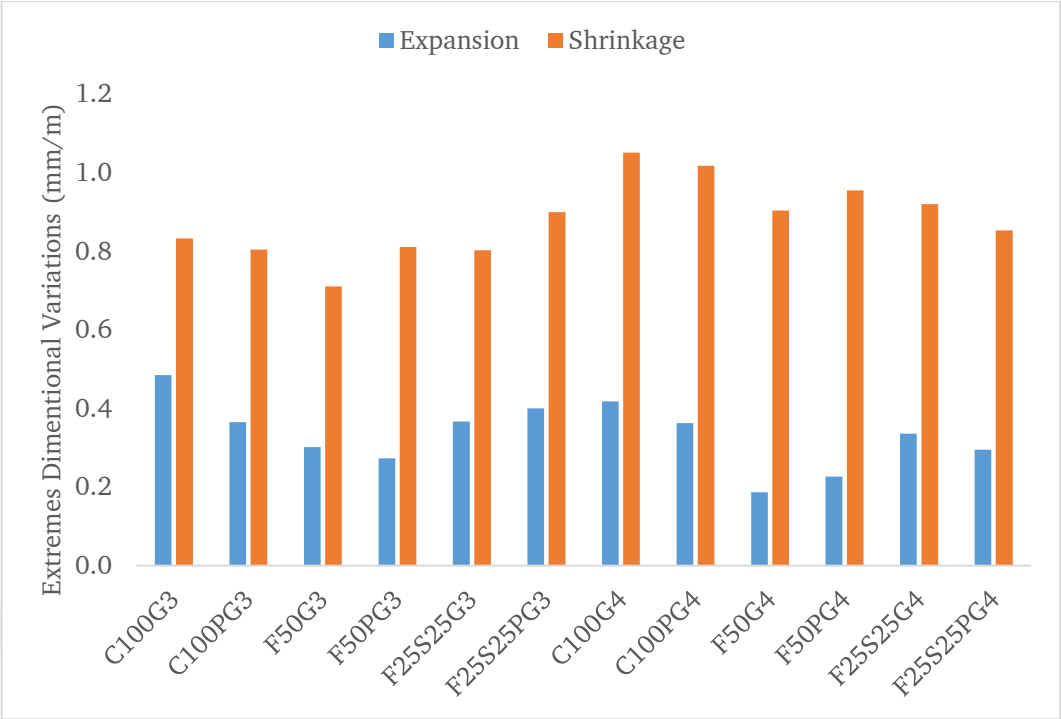


Figure 4.6 Expansion and shrinkage values of the GFRC mixes

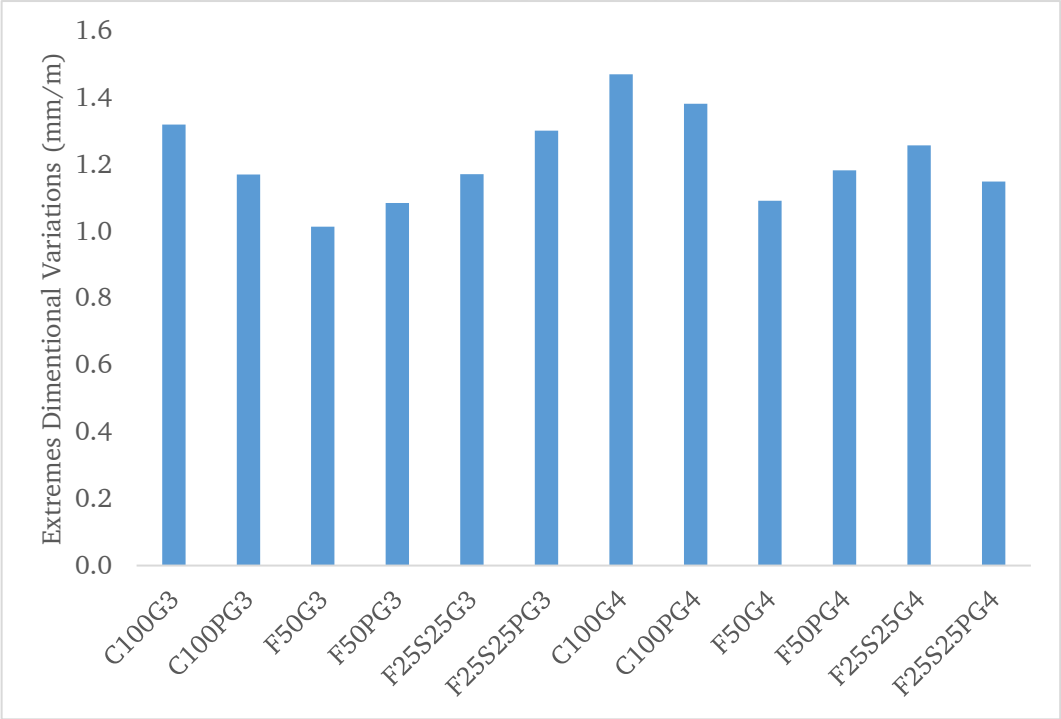


Figure 4.7 Extreme dimensional variations due to shrinkage and expansion

4.3 Mechanical Tests

4.3.1 Matrix Properties

The flexural strength development of the matrix phase of GFRC mixes is shown in Fig. 4.8. Mixtures containing fly ash and slag showed lower strength compared to the reference mixtures. However, the strength development of the matrix mixes incorporating fly ash and slag show significant strength increase, especially at 90 days.

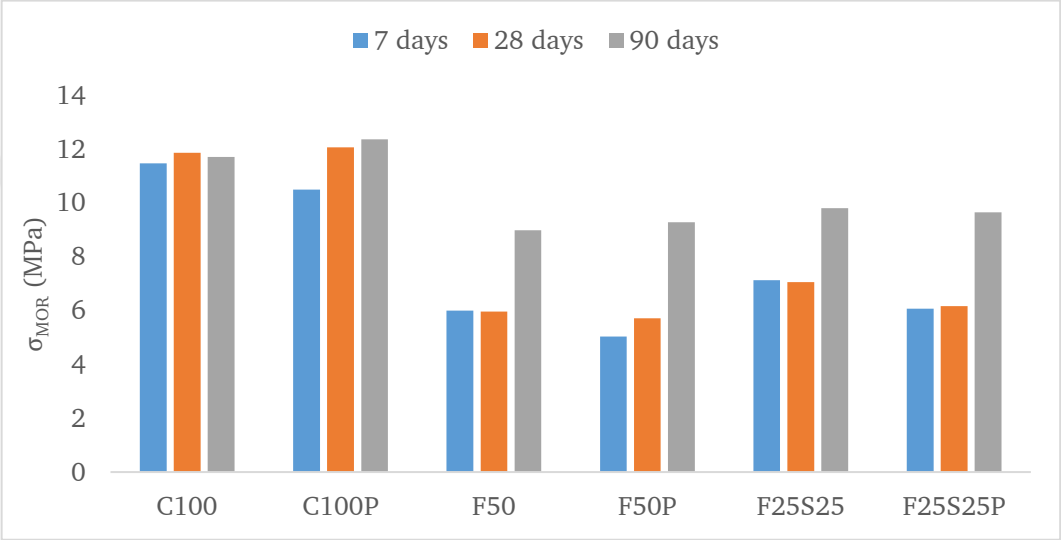


Figure 4.8 Flexural strength development of the matrix

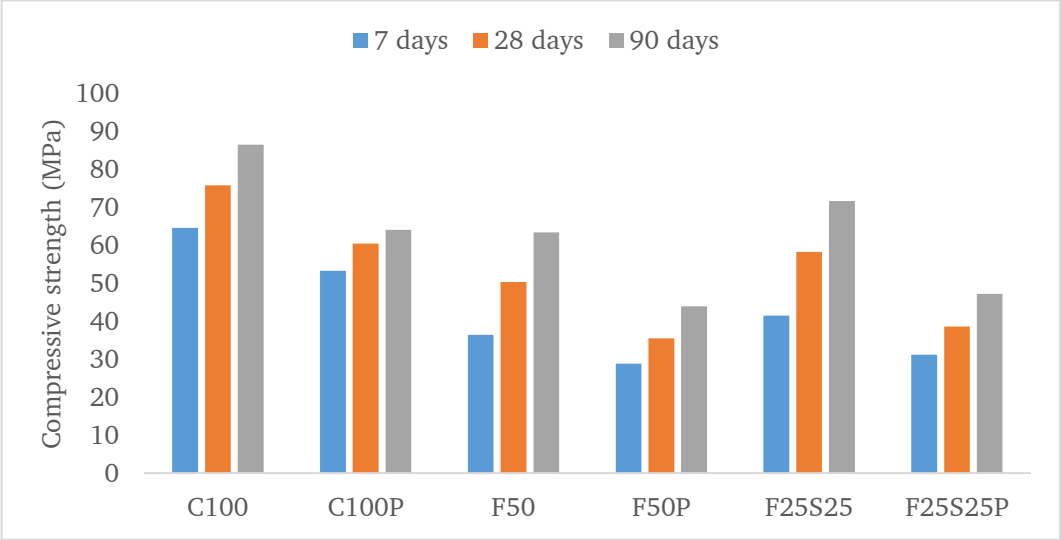


Figure 4.9 Compressive strength development of the matrix

The average of compressive strength results is shown in Fig. 4.9. The compressive strength of the mixtures consistently improved with curing time. Polymer addition reduced the compressive strength. The compressive strength values of the mixes containing pozzolanic materials were found to be lower than those of the reference mixtures.

4.3.2 Flexural Properties of GFRC

Flexural strength is the most important property that represents the quality of GFRC. In this study, flexural tests were performed at 7, 28 and 90 days. The average of the flexural test results of GFRC mixtures are shown in Figs. 4.10 and 4.11. Deformation at limit of proportionality (ε_{LOP}), deformation at failure (ε_{MOR}), stress at limit of proportionality (σ_{LOP}), and stress at failure (σ_{MOR}) values are also presented in Tables 4.2-4.4.

The test results show that the flexural strength (σ_{MOR}) of the reference mixes are higher than those containing pozzolanic materials. The highest flexural strength was found as 15.08 MPa in C100P5G3 mix at 90 days. Polymer addition slightly affected the flexural strength of the mixes. The increase in fiber content, did not improve the flexural strength of reference mixtures, however the flexural strength of mixes incorporating fly ash and slag improved significantly with increasing fiber content.

The variation of deformations (ε_{LOP} and ε_{MOR}) showed no clear trend with age, while in some mixes the deformations were improved, on the other hand, in some mixes deformations were reduced or no significant change was observed. The relationship between σ_{LOP} and σ_{MOR} is shown in Fig. 4.12, which presents that the both factors are correlated quite well with each other representing R^2 of 0.86.

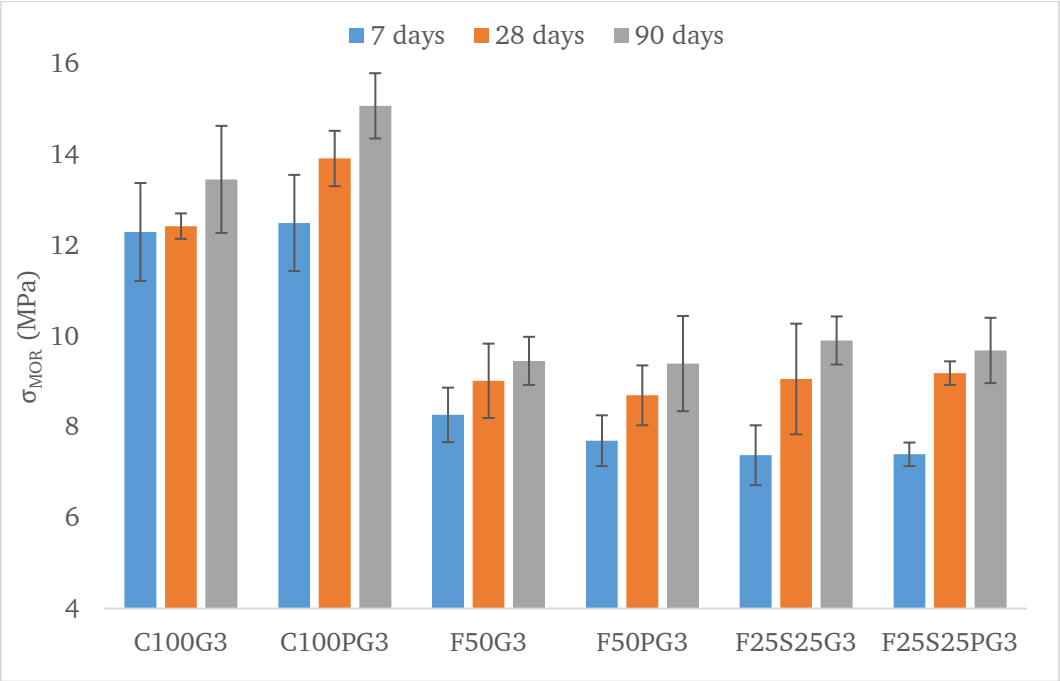


Figure 4.10 Flexural strength development of GFRC mixes with 3% fiber

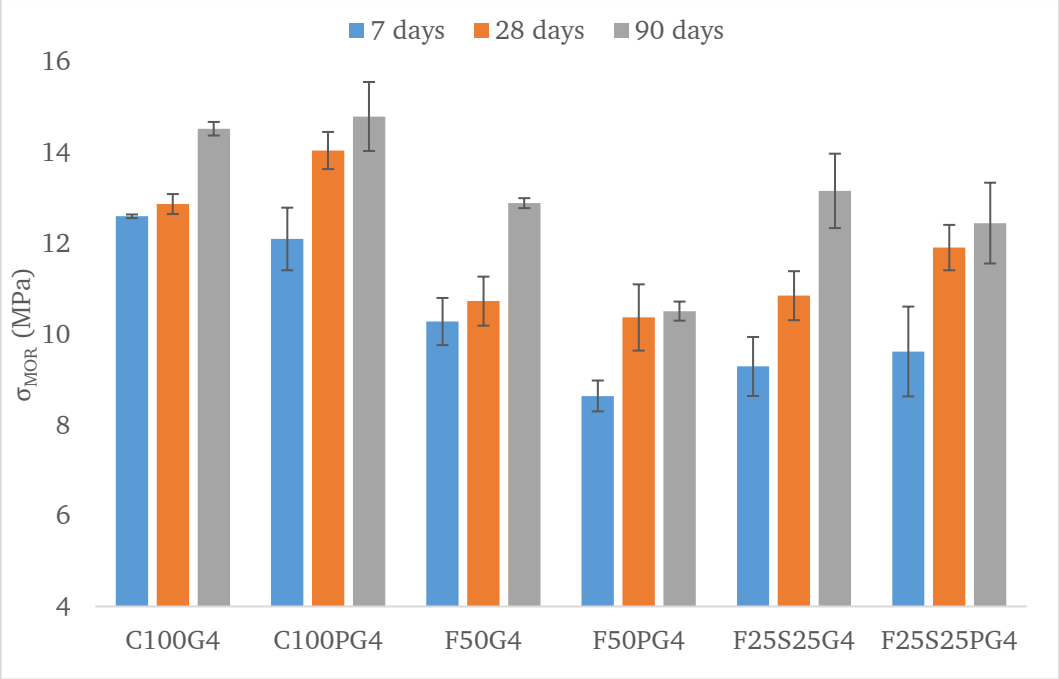


Figure 4.11 Flexural strength development of GFRC mixes with 4% fiber

Table 4.2 Stress and deformation values of GFRC mixes at 7 days

Mixtures	ε_{LOP}	ε_{MOR}	σ_{LOP} (MPa)	σ_{MOR} (MPa)
C100G3	0.047	0.402	9.43	12.30
C100P5G3	0.077	0.445	10.14	12.50
F50G3	0.056	0.395	5.91	8.27
F50P5G3	0.050	0.532	5.48	7.70
F25S25G3	0.040	0.282	6.34	7.38
F25S25P5G3	0.046	0.315	6.85	7.40
C100G4	0.060	0.410	9.41	12.60
C100P5G4	0.068	0.456	10.74	12.10
F50G4	0.056	0.409	7.44	10.28
F50P5G4	0.057	0.571	6.37	8.64
F25S25G4	0.035	0.306	6.17	9.29
F25S25P5G4	0.051	0.381	7.27	9.62

Table 4.3 Stress and deformation values of GFRC mixes at 28 days

Mixtures	ε_{LOP}	ε_{MOR}	σ_{LOP} (MPa)	σ_{MOR} (MPa)
C100G3	0.042	0.321	10.34	12.43
C100P5G3	0.077	0.442	10.80	13.92
F50G3	0.042	0.203	6.36	9.02
F50P5G3	0.060	0.470	6.85	8.70
F25S25G3	0.035	0.271	6.60	9.06
F25S25P5G3	0.057	0.294	8.36	9.19
C100G4	0.075	0.423	10.04	12.87
C100P5G4	0.063	0.438	10.70	14.05
F50G4	0.052	0.329	7.67	10.73
F50P5G4	0.083	0.576	7.72	10.37
F25S25G4	0.055	0.325	8.37	10.85
F25S25P5G4	0.047	0.475	9.05	11.91

Table 4.4 Stress and deformation values of GFRC mixes at 90 days

Mixtures	ε_{LOP}	ε_{MOR}	σ_{LOP} (MPa)	σ_{MOR} (MPa)
C100G3	0.042	0.231	10.07	13.46
C100P5G3	0.068	0.562	11.36	15.08
F50G3	0.030	0.236	7.93	9.46
F50P5G3	0.075	0.502	6.51	9.40
F25S25G3	0.062	0.219	9.42	9.91
F25S25P5G3	0.056	0.364	8.05	9.69
C100G4	0.085	0.336	11.66	14.53
C100P5G4	0.083	0.407	11.21	14.80
F50G4	0.081	0.337	10.24	12.89
F50P5G4	0.078	0.496	8.21	10.51
F25S25G4	0.057	0.370	9.34	13.16
F25S25P5G4	0.070	0.607	8.80	12.45

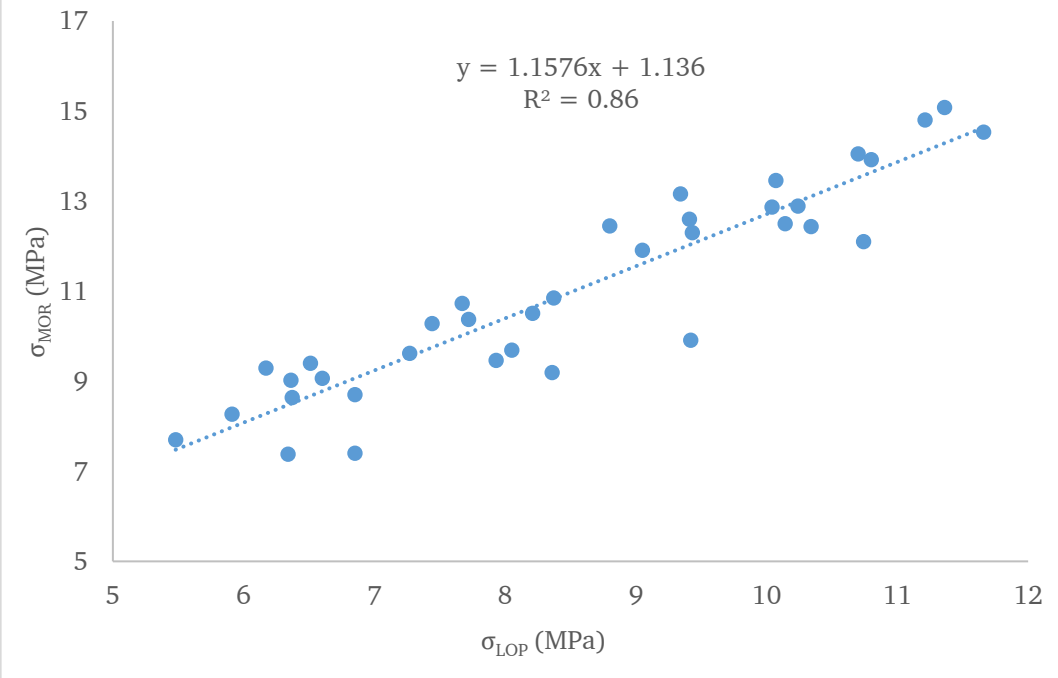


Figure 4.12 Relationship between σ_{LOP} and σ_{MOR}

The bending behavior of the GFRC is generally categorized as deflection-hardening or deflection-softening. GFRC products performing deflection-hardening behavior offer high load-bearing capacity compared to those performing deflection softening following the first crack [51]. Load-deflection curves of mixes in Figs 4.13-4.18 shows that the GFRC mixes yield deflection-hardening behavior. The behavior following the initial crack (LOP) up to fracture provides important information about the material's plastic deflection capability. Figs. 4.19-4.21 shows the plastic deflection of GFRC mixes obtained by considering the deflection from LOP point up to the deflection point corresponding to 75% of the post peak load. The plastic deflection capability of the mixes is consistently increased with acrylic polymer inclusion. The increase in fiber content also resulted in slight increase in the plastic deflection of all mixes.

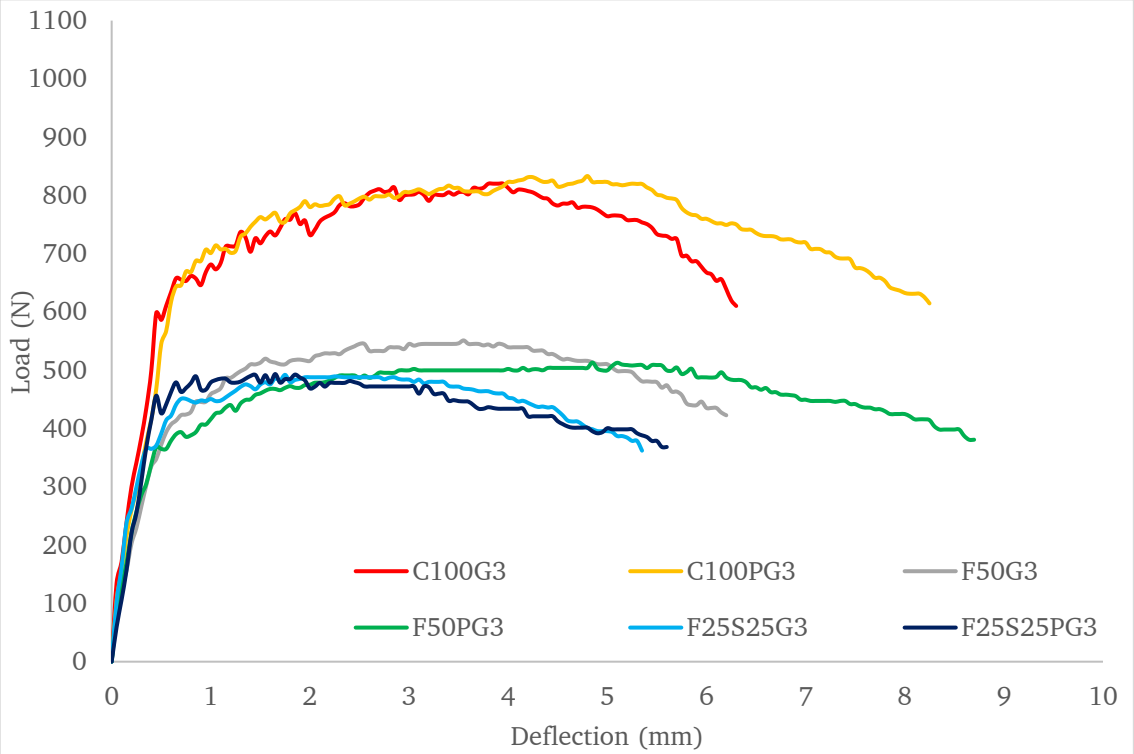


Figure 4.13 Load-Deflection curve of GFRC mixes with 3% fiber at 7 days

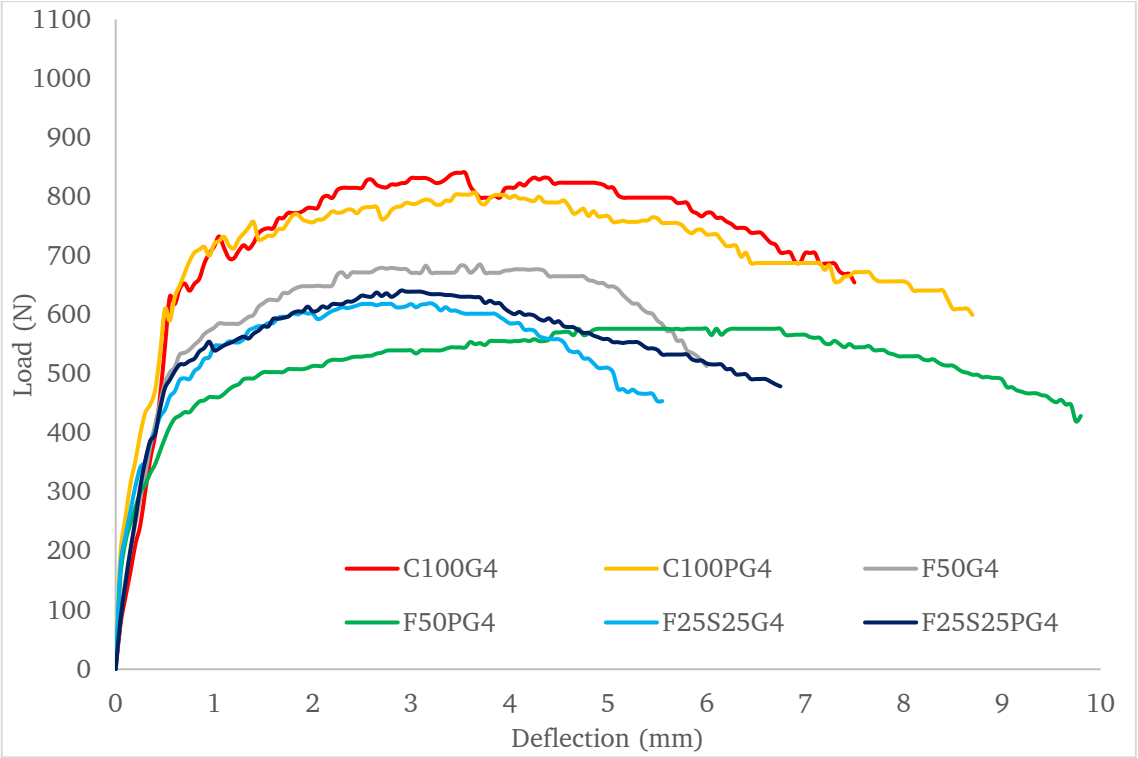


Figure 4.14 Load-Deflection curve of GFRC mixes with 4% fiber at 7 days

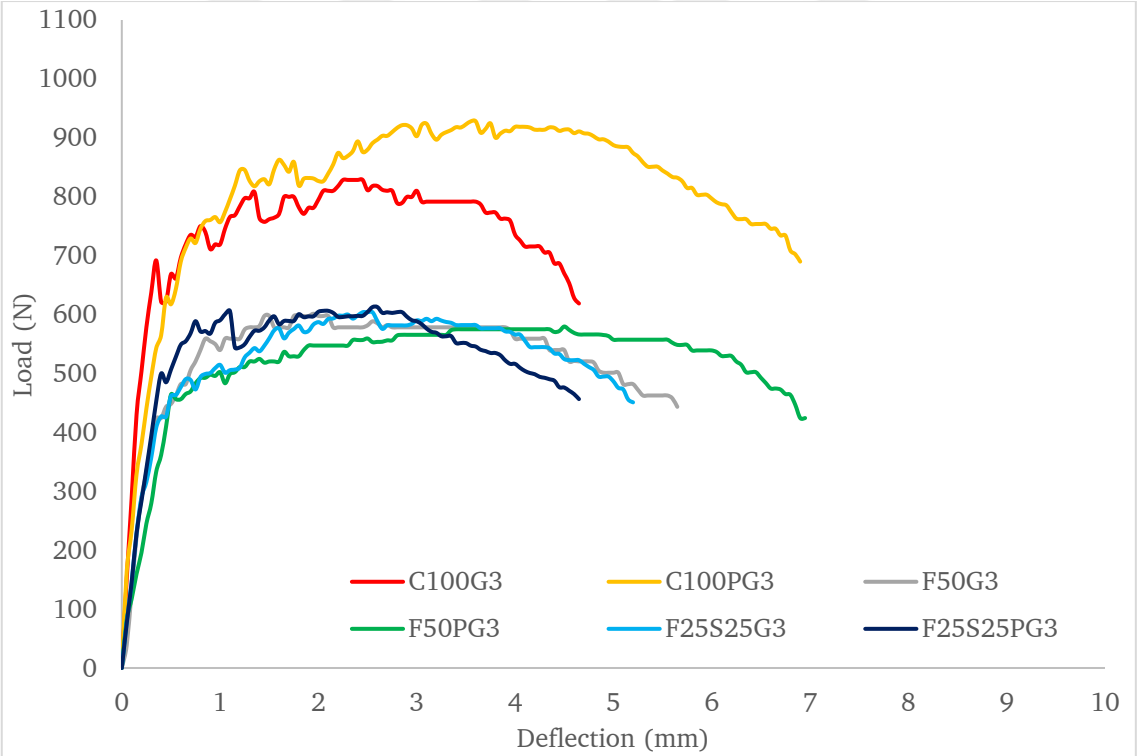


Figure 4.15 Load-Deflection curve of GFRC mixes with 3% fiber at 28 days

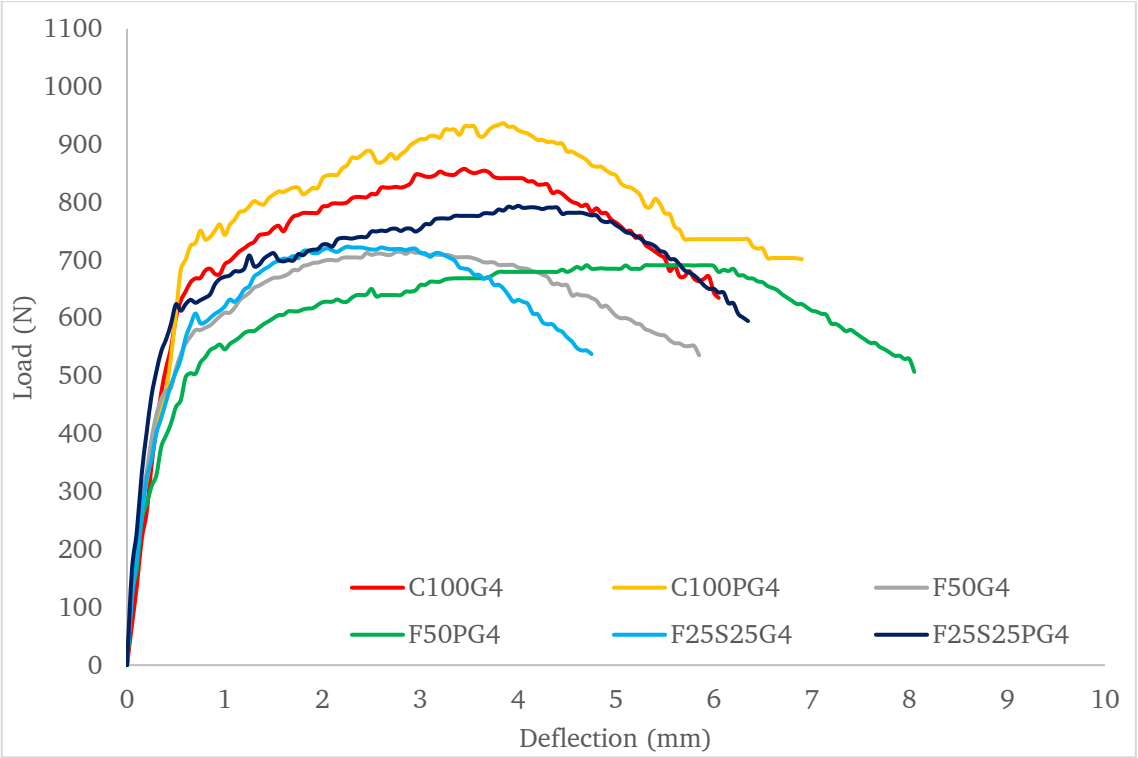


Figure 4.16 Load-Deflection curve of GFRC mixes with 4% fiber at 28 days

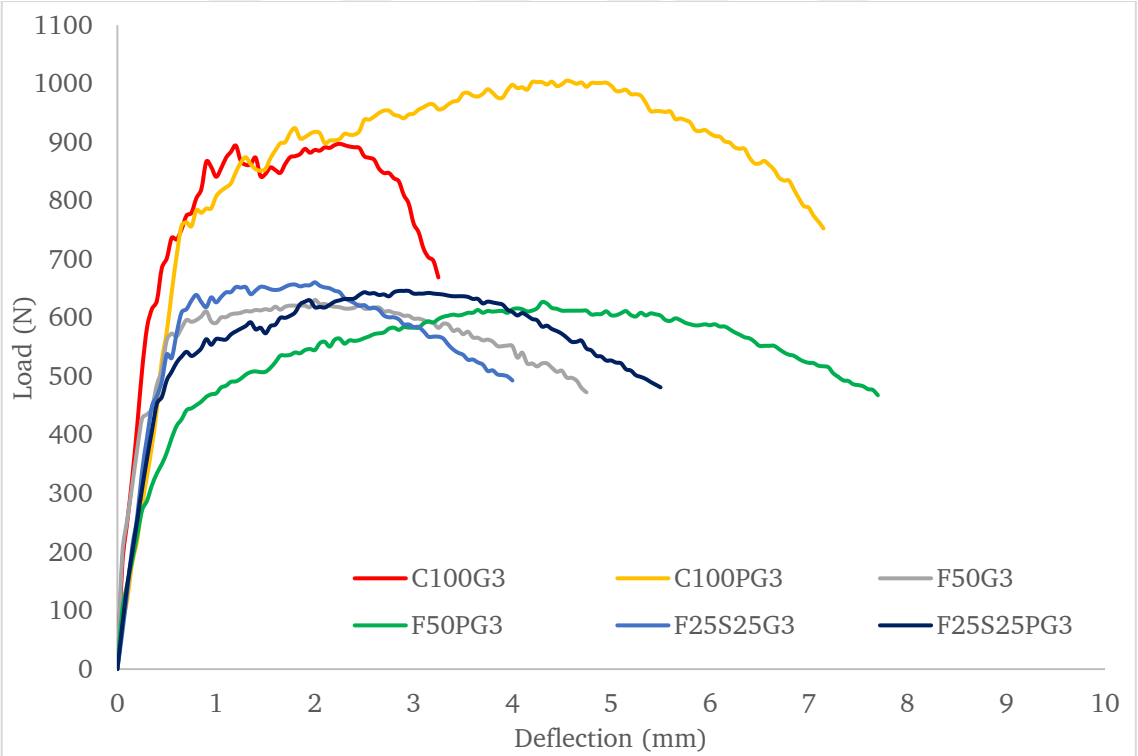


Figure 4.17 Load-Deflection curve of GFRC mixes with 3% fiber at 90 days

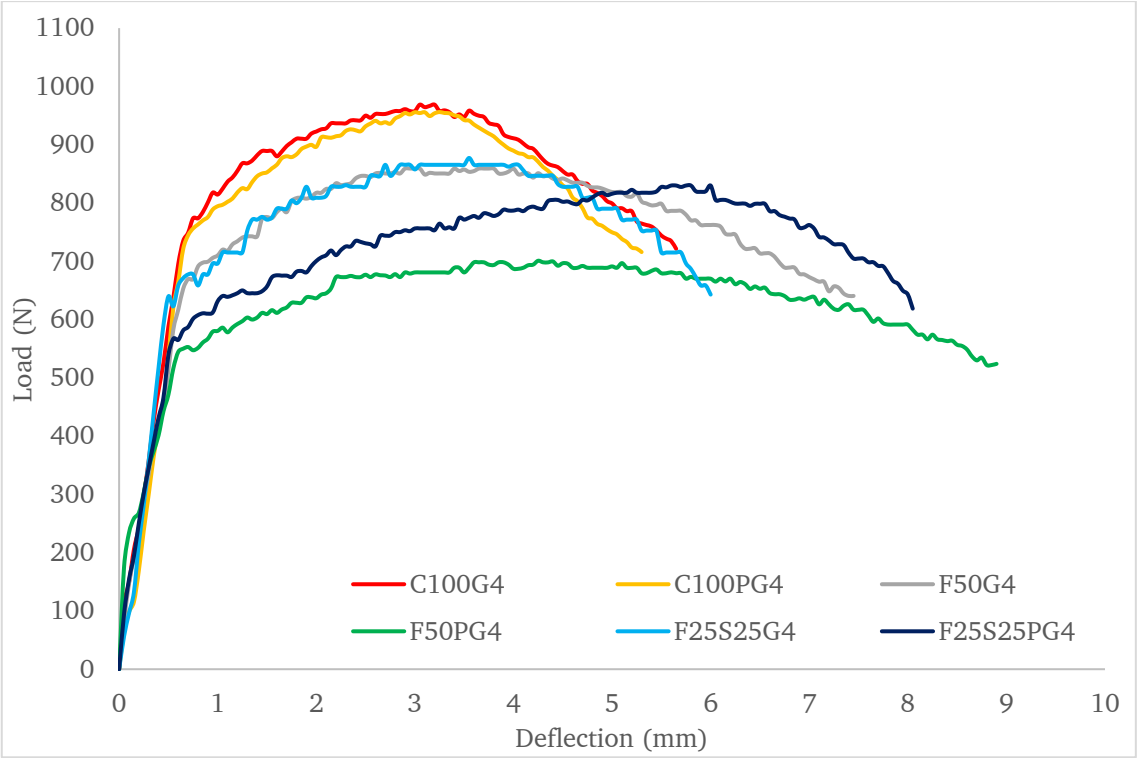


Figure 4.18 Load-Deflection curve of GFRC mixes with 4% fiber at 90 days

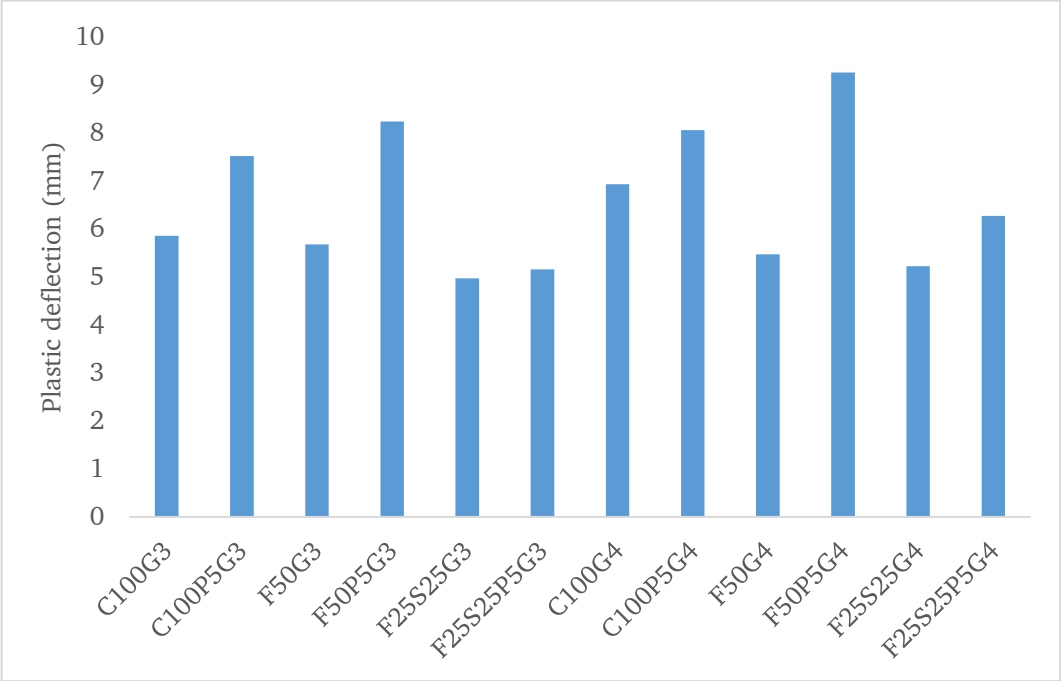


Figure 4.19 Plastic deflection of GFRC mixes at 7 days

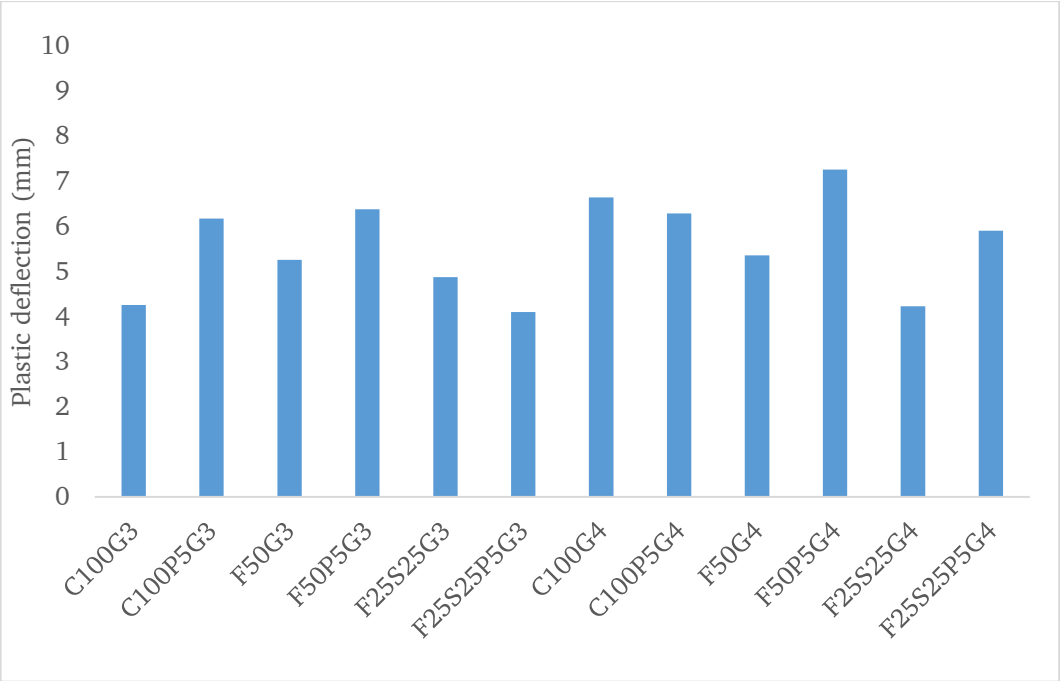


Figure 4.20 Plastic deflection of GFRC mixes at 28 days

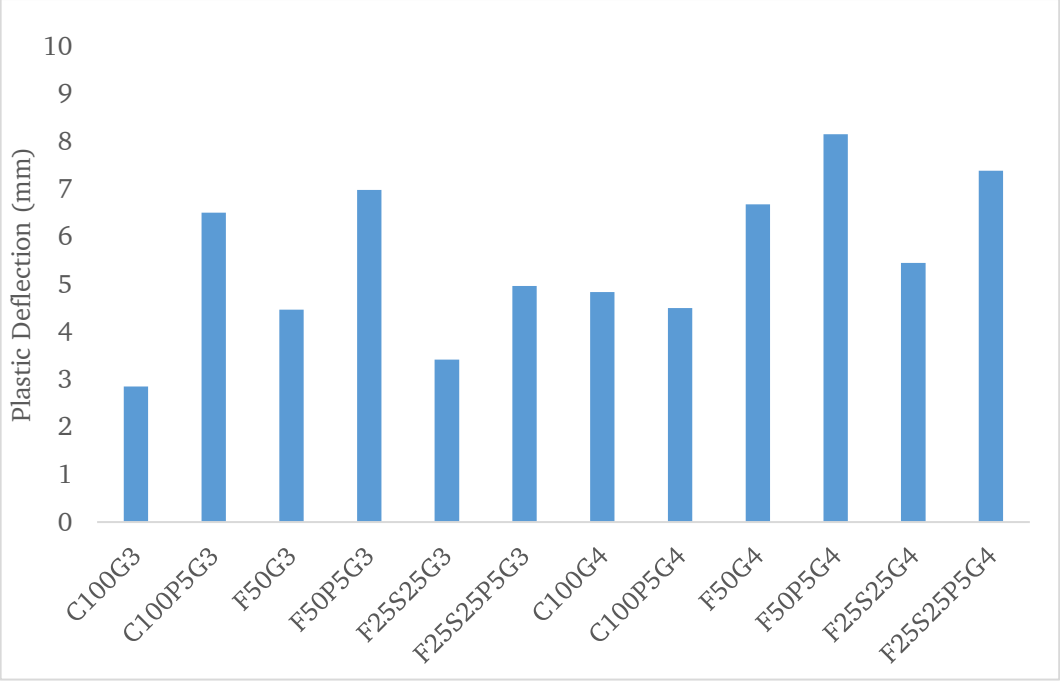


Figure 4.21 Plastic deflection of GFRC mixes at 90 days

The flexural strength improvement ratios of GFRC mixtures compared to matrix mixes are shown in Figs. 4.22 and 4.23. The addition of fiber to the mixtures increased the flexural strength as well as the increase in the fiber content further improved the flexural strength. Improvement ratio is particularly high in mixes

incorporating pozzolanic materials compared to the reference mixes, especially at 4% fiber ratio, reaching up to 93% in F25S25PG4 mix.

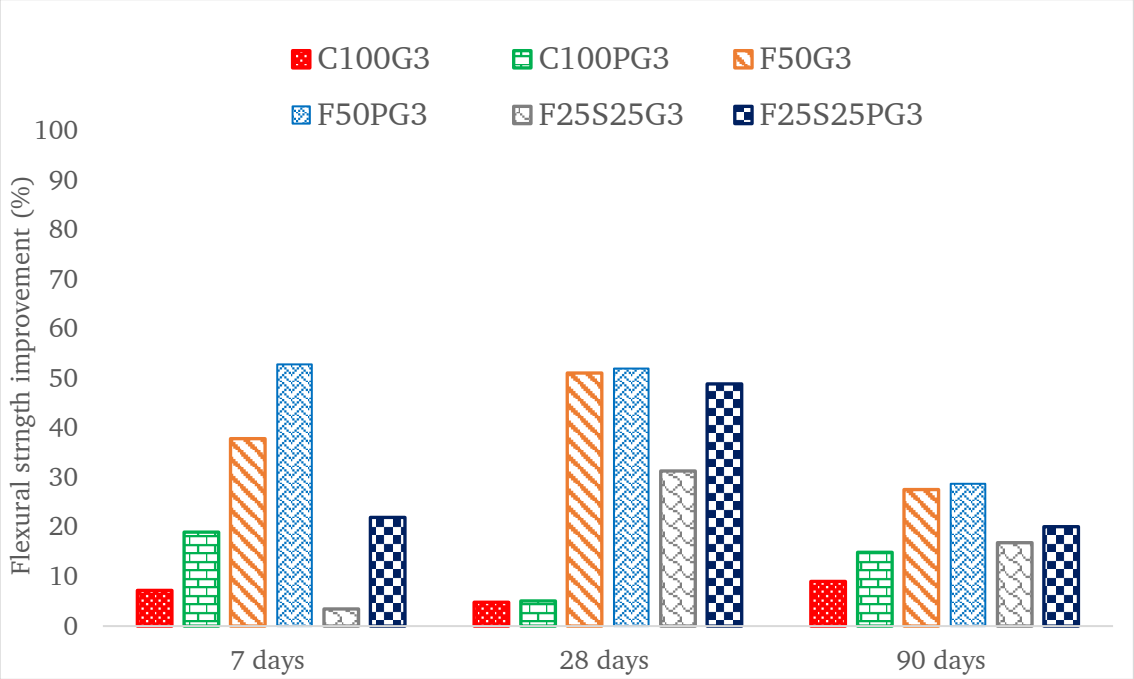


Figure 4.22 Flexural strength improvement of GFRC mixes with 3% fiber

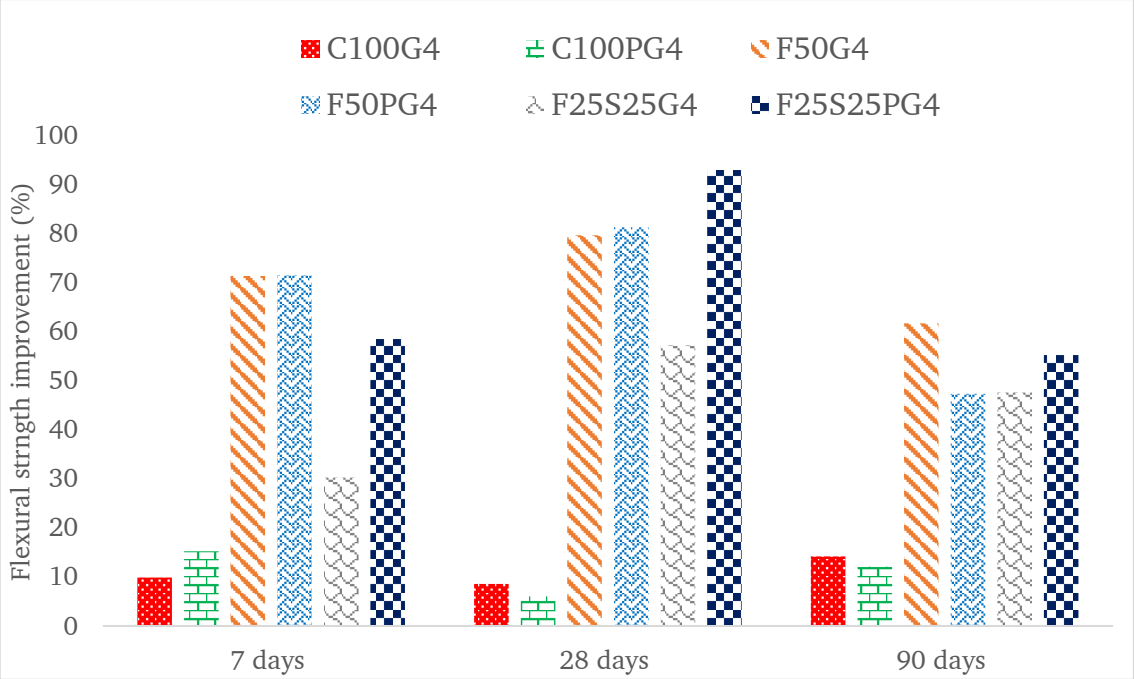


Figure 4.23 Flexural strength improvement of GFRC mixes with 4% fiber

The failure modes of the matrix and GFRC are shown in Figs 4.24 and 4.25. During the flexural testing, the failure in the matrix samples occurred in a brittle manner just after the initial cracks formed, as expected. On the other hand, GFRC samples continued to carry load after the initial crack formation and exhibited a ductile behavior, as desired.

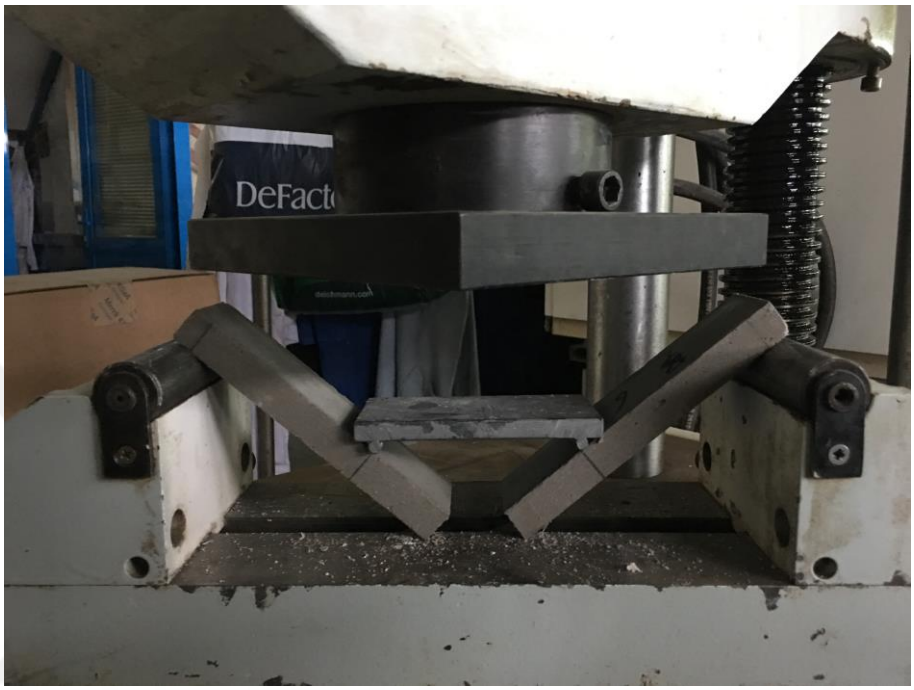


Figure 4.24 Behavior of the matrix sample under load



Figure 4.25 Behavior of the GFRC sample under load

4.4 Toughness

The main constituents of GFRC are cement-based matrices and glass fibers, both are in nature brittle materials. The combination of these materials is also expected to be brittle. Fiber reinforcement in GFRC consists of bundles, each containing many individual fibers. The bond between the matrix and the fibers and between the fibers itself is in such a way that applied load generates complex stresses and displacements that give the composite a degree of inelastic behavior; a pseudo-ductility is observed. Therefore, GFRC is more impact resistant than plain concrete and many other fiber-reinforced composites. Longer fibers allow the fracture mechanism to break fibers instead of fiber pullout. This explains the high toughness values obtained in the sprayed GFRC, where longer fibers are used. A tough composite generally exhibits significant deformations before a final break, which in some way is a warning before a failure in applications [1].

GFRC loses strength and toughness when exposed to humid environments [52]. In order to reduce losses in strength and toughness, different materials were used as a replacement of cement. Marikeunte [53], found that the use of metakaolin resulted in a decrease in toughness while improving the durability of GFRC exposed to accelerated ageing. Similar results were obtained by other studies with the addition of metakaolin and polymer [54]–[56]. Many researchers reported that fly ash was found to improve durability. However, it has been reported that substituting high amounts of cement with fly ash decreases toughness after ageing [28], [29], [57]–[59].

The toughness values of GFRC mixes are shown in Figs. 4.26 and 4.27. The figures show that the toughness of the reference mixes was not improved by age, even in some cases dropped at 28 days. On the other hand, the toughness slightly improved with age in mixes incorporating fly ash and slag. The addition of acrylic polymer consistently resulted in clear increase in toughness values in all mixes. The increase in fiber content also improved the toughness values of the mixtures, the exception was the reference mixtures where no significant change was observed.

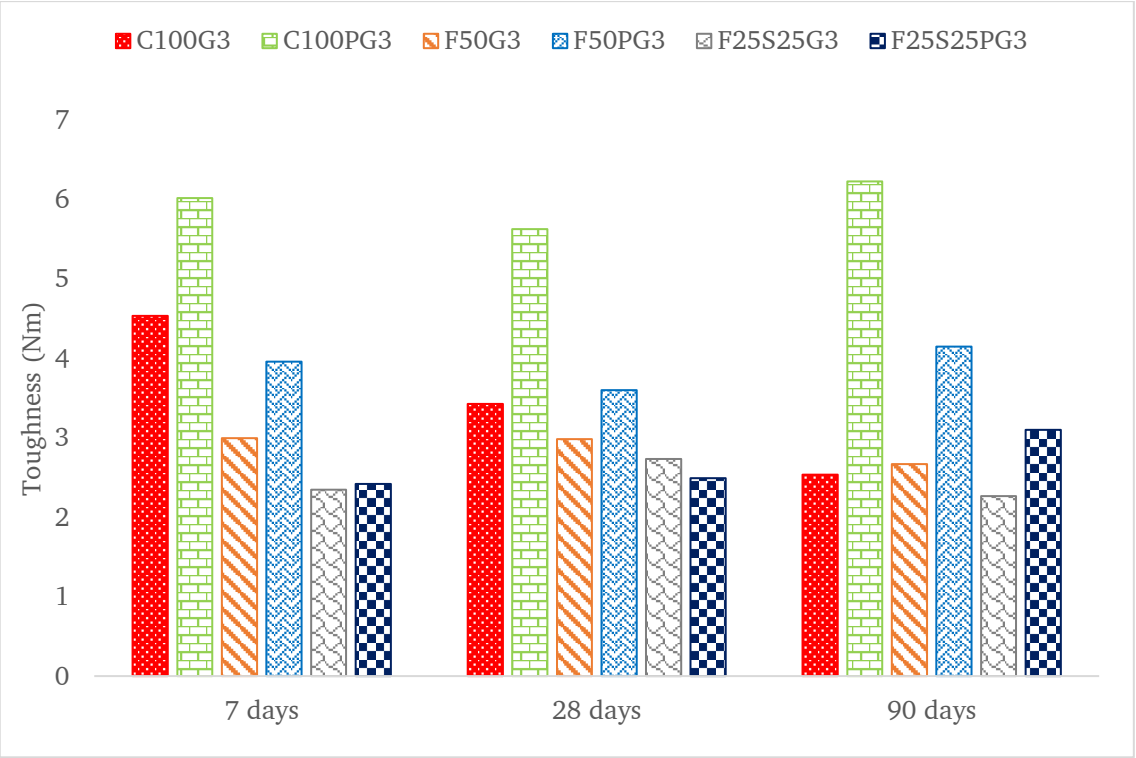


Figure 4.26 Toughness of GFRC mixes with 3% glass fiber

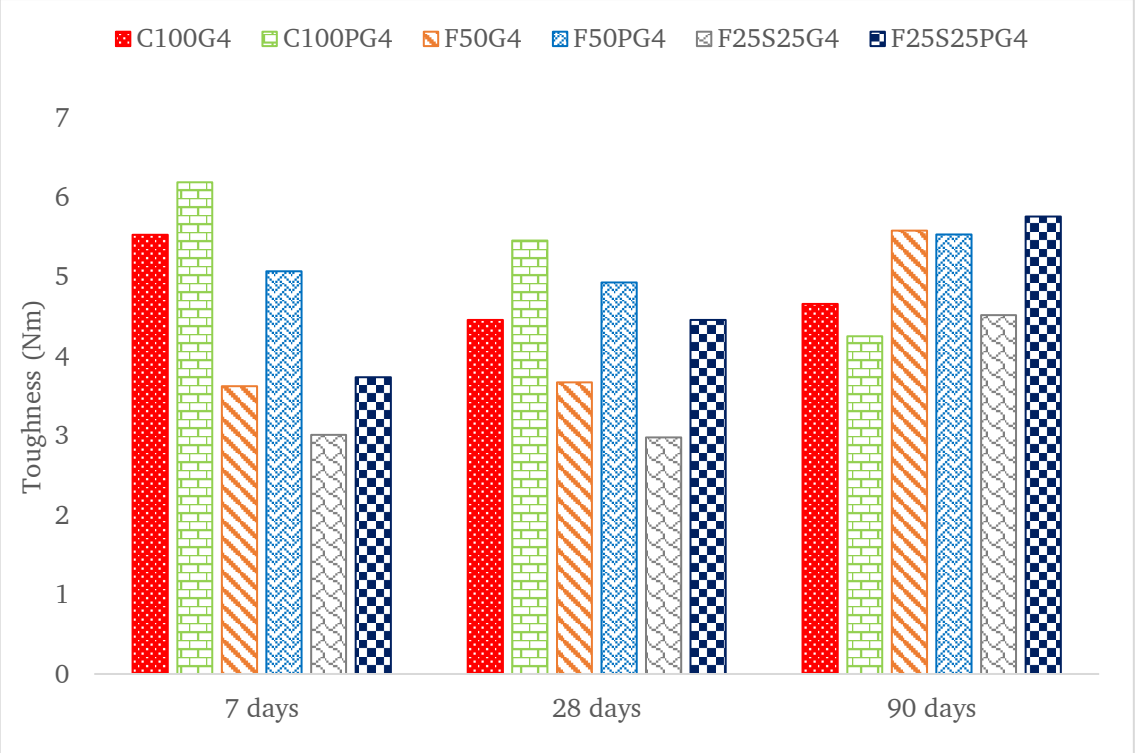


Figure 4.27 Toughness of GFRC mixes with 4% glass fiber

4.5 Durability Tests

4.5.1 Freeze/Thaw Cycles

The freeze-thaw test results are shown in Fig. 4.28. Flexural strength of C100G3, C100PG3, and C100PG4 reference mixes remained similar after the freeze/thaw cycles. On the other hand, in addition to withstanding freeze/thaw cycles, there is an increase of 23% in flexural strength of C100G4 mixes with 4% fiber content. The mixes F50G3, F50PG3, F50G4 and F50PG4 with fly ash presented an improvement ratio of 17-39% in flexural strength after 25 cycles. F25S25PG3, F25S25G4 and F25S25PG4 mixes with blast furnace slag and fly ash presented improvement from 12% to 34% after 25 cycles in flexural strength.

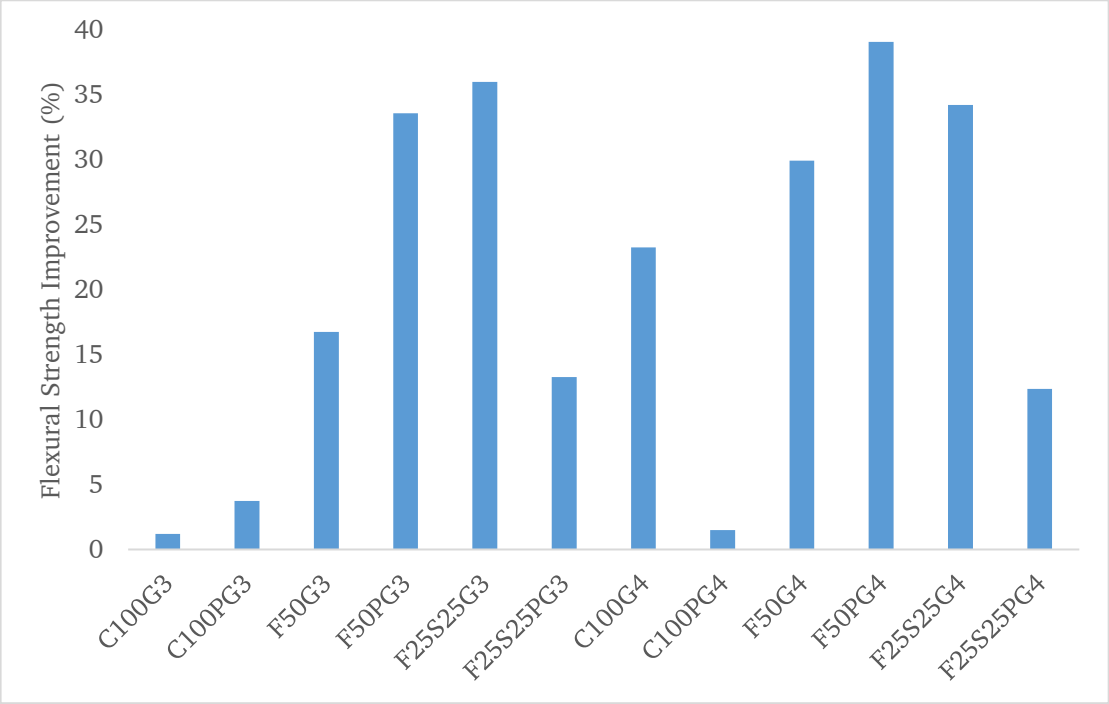


Figure 4.28 Flexural strength change of GFRC mixes exposed to freeze-thaw cycles

Test results indicate that GFRC can withstand frost action without suffering any damage, and in most cases flexural strength was significantly improved with fly ash and slag addition. Similar results can be found in the literature [6].

4.5.2 Cyclic Weathering Test

The flexural strength results of the GFRC mixtures exposed to wet-dry cycles are shown in Figs. 4.29 and 4.30. Wet-dry cycles significantly reduced the mechanical performance of all GFRC mixes. This effect is observed to be less in the mixes incorporating pozzolanic materials and acrylic polymer. The normalized residual flexural strength results are plotted in Fig. 4.31. The figure shows that the combination of fly ash, slag and acrylic polymer improved the durability of the mixes exposed to wet/dry cycles. The highest performance was observed in F25S25PG3 and F25S25PG4 mixes, while the C100PG3 mix showed the lowest performance, losing about 45% of its flexural strength after the exposure.

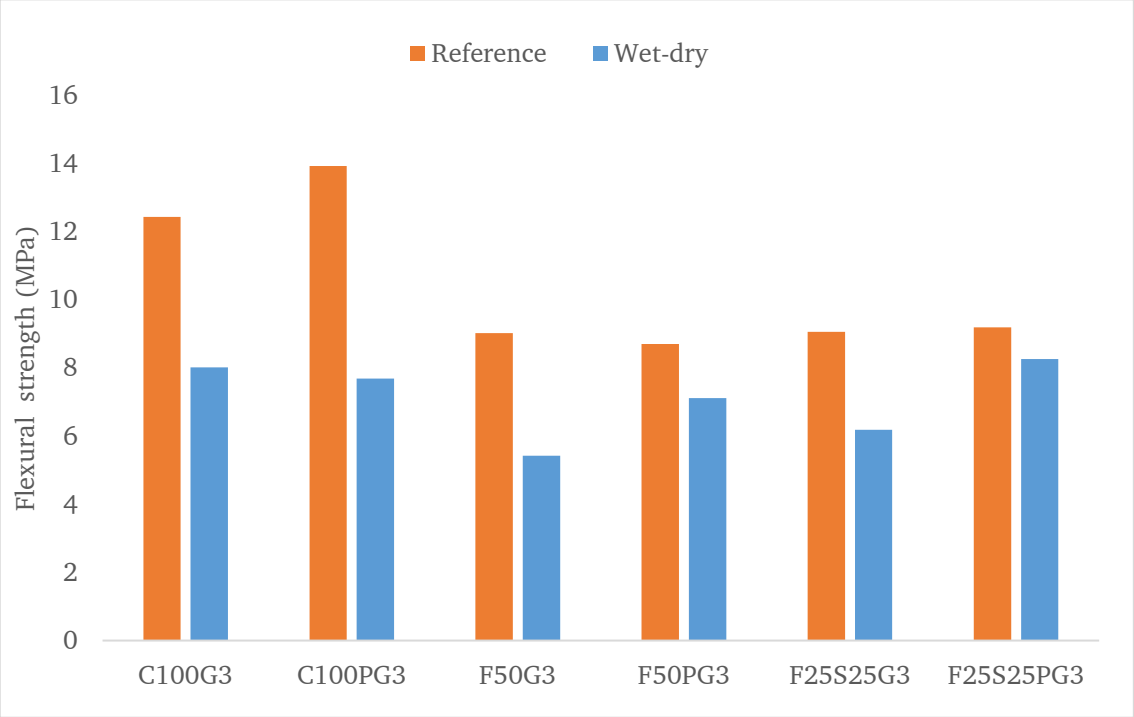


Figure 4.29 Flexural strength of GFRC mixes with 3% fiber exposed to wet-dry cycles

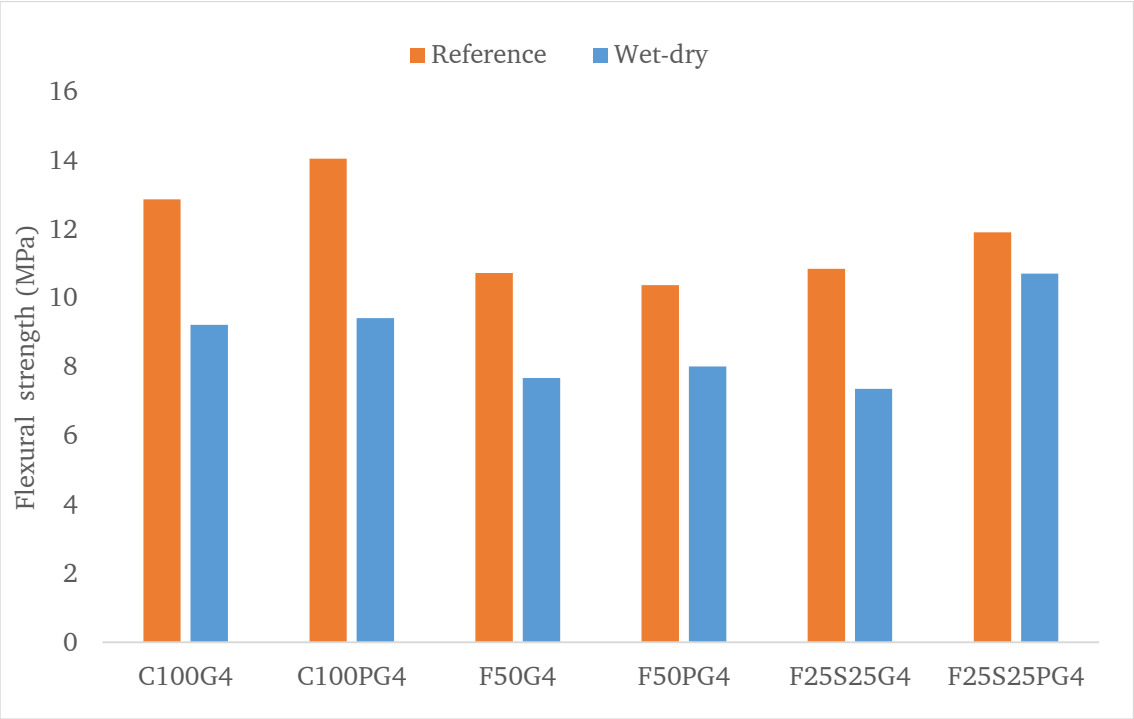


Figure 4.30 Flexural strength of GFRC mixes with 4% fiber exposed to wet-dry cycles

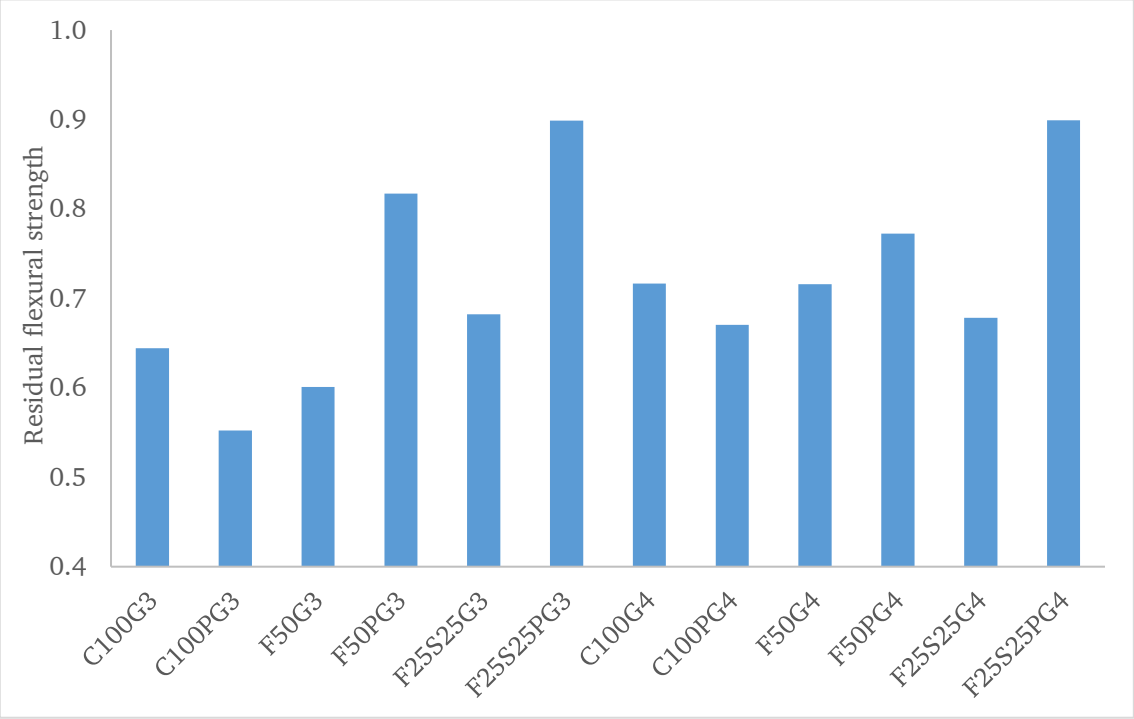


Figure 4.31 Normalized residual flexural strength of GFRC mixes exposed to wet-dry cycles

4.5.3 High Temperature Test

The damage of GFRC mixes due to high temperature can be explained by three mechanism: (i) the damage in the matrix phase, (ii) the damage in the fibers, and (iii) the damage between fiber and matrix interface.

With the elevation of temperature, concrete experiences several physical and chemical changes which in turn causes changes in the mechanical properties. At about 105°C, hydration products lose their free water and physically absorbed water completely and start to lose their chemically bonded and at 400°C capillary water is lost completely. Calcium hydroxide starts to decompose at about 350-500°C. C–S–H starts to decompose at around 560°C, decomposes into β-C_2S at around 600–700°C and on the order of 900°C complete decomposition of the C-S-H occurs. During 580–900°C, decarbonation of carbonates occurs. The differential thermal strain between aggregates and the cement paste at elevated temperatures induces development of micro-cracks. As a result of the increased porosity and micro-crack formation, the mechanical properties of the matrix phase gradually reduces with increase temperature [60], [61].

Glass in general softens with temperature starting from approximately 200–700°C and its mechanical properties are changed with elevated temperature [1]. The AR glass fiber is reported to have softening temperature of about 800°C, and therefore reductions in its mechanical properties might be expected around this temperature which may also reduce the contribution of fibers to mechanical performance of GFRC mixes.

The bond between glass fiber and the matrix phase plays an important role in the mechanical behavior of GFRC. Since high temperature induces cracks and increases the porosity of the matrix, the bond between fiber and matrix is expected to be reduced, causing drops in the mechanical properties of GFRC mixtures.

Flexural strength of GFRC mixes exposed to high temperatures are shown in Figs. 4.32 and 4.33.

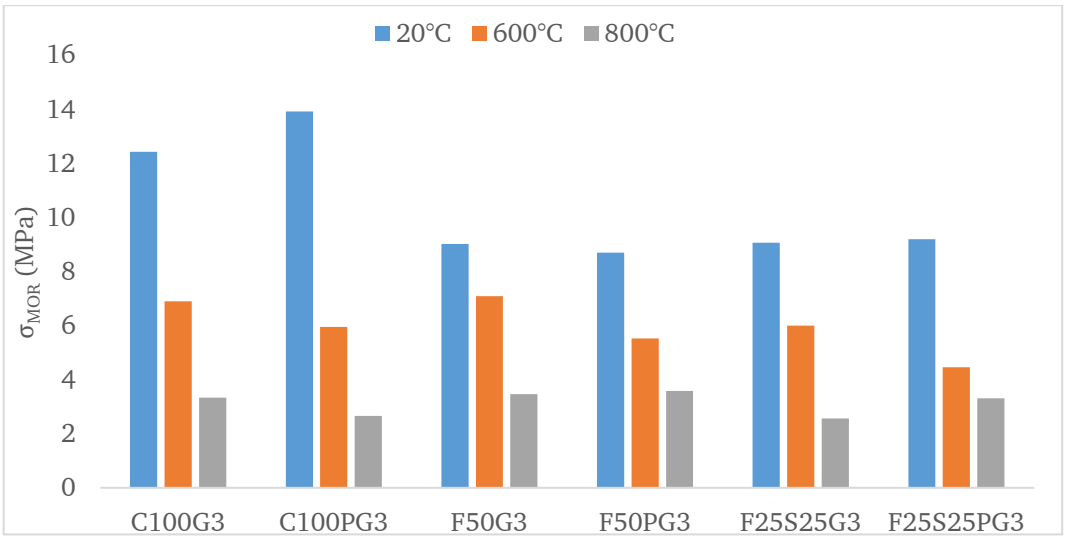


Figure 4.32 Flexural strength of GFRC with 3% fiber exposed to high temperatures

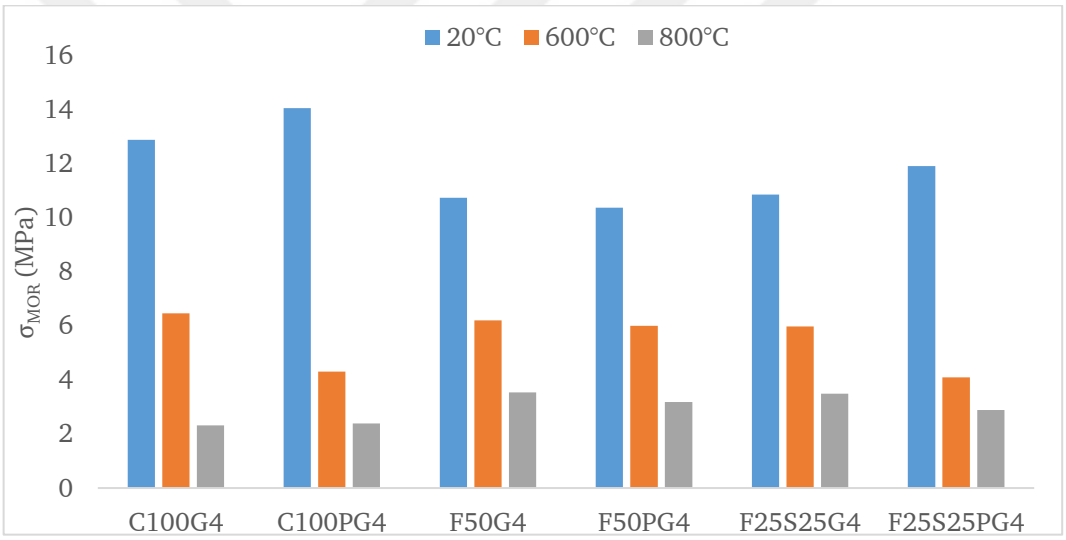


Figure 4.33 Flexural strength of GFRC with 4% fiber exposed to high temperatures

Normalized residual flexural strength of the mixes are also shown in Figs. 4.34 and 4.35. The test results show that the flexural strength of the mixes is reduced when exposed to high temperatures of 600 and 800°C, the higher the exposed temperature resulted in higher drops in strength of all mixes. However, the substitution of cement with fly ash improved the durability against high temperature effect. The loss in flexural strength of F50G3 mix was found as 14% and 42% after exposed to 600 and 800°C, respectively. The reference mixture,

C100G3, suffered a higher loss in flexural strength (44 and 50%). The addition of acrylic polymer was found to increase the damage due to high temperature. The increase in the fiber content from 3 to 4% also resulted in greater strength reductions of mixes after high temperature.

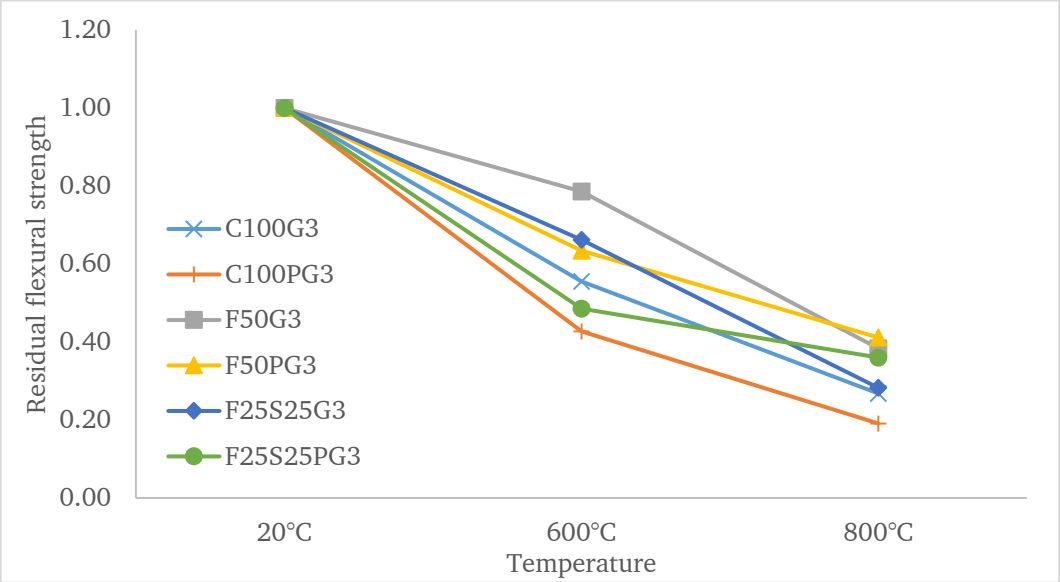


Figure 4.34 Normalized residual flexural strength of GFRC mixes with 3% fiber exposed to high temperature

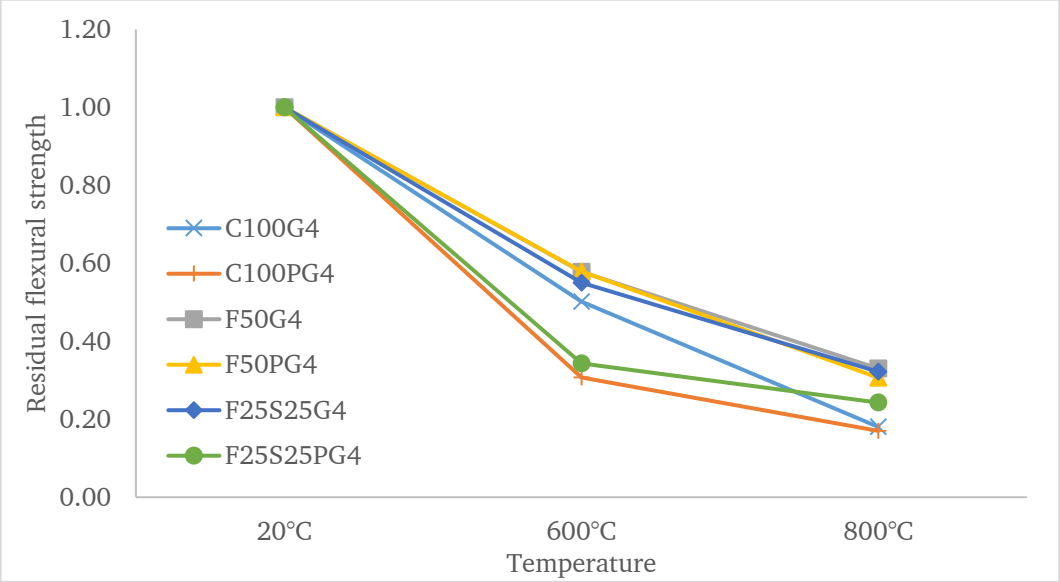


Figure 4.35 Normalized residual flexural strength of GFRC mixes with 4% fiber exposed to high temperature

Crack formation on the surface of the tested specimens after exposure to elevated temperatures are visualized by a stereo zoom microscope and the images taken are shown in Figs. 4.36-4.41. No crack formation was observed on mixes C100PG3 F50PG3, F25S25G3, F25S25PG3, F50PG4, and F25S25PG4. C100G3, F50G3, and C100G4 mixes showed no visible cracks at 600°C, but significant crack patterns were observed at 800°C. In the reference mixtures, C100G3 and C100G4, large cracks with a width of 50-145μm were noticed after exposure to 800°C. In C100G4 mix, several narrow cracks have formed with different widths along with larger cracks. The crack width observed in F50G3 mix varied between 2-20μm. In C100PG4 mix the crack width was between 10-40μm and 50-175μm at 600 and 800°C, respectively. The cracks widths in F50G4 and F25S25G4 mixes varied between 5-30μm at 800°C and no crack formation was observed at 600 °C



Figure 4.36 Image of C100G3 mix exposed to 600°C (left) and 800°C (right)

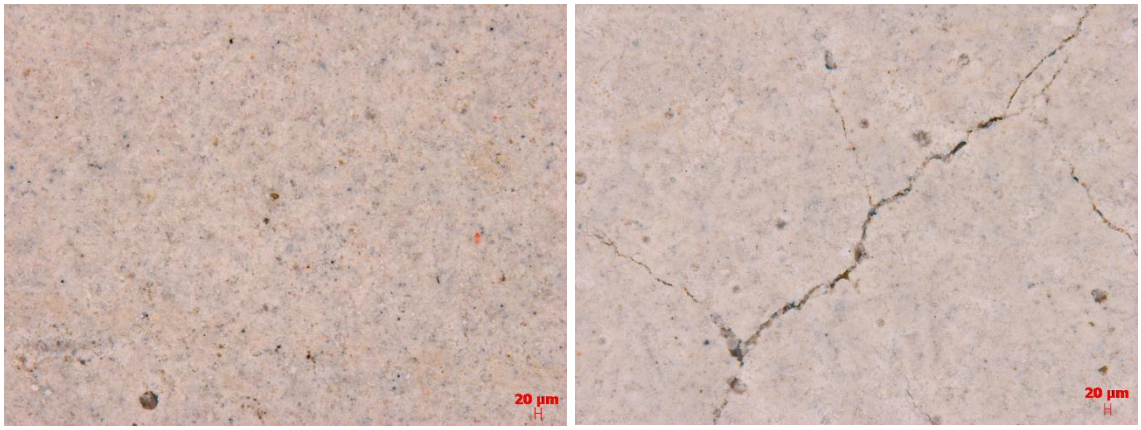


Figure 4.37 Image of F50G3 mix exposed to 600°C (left) and 800°C (right)

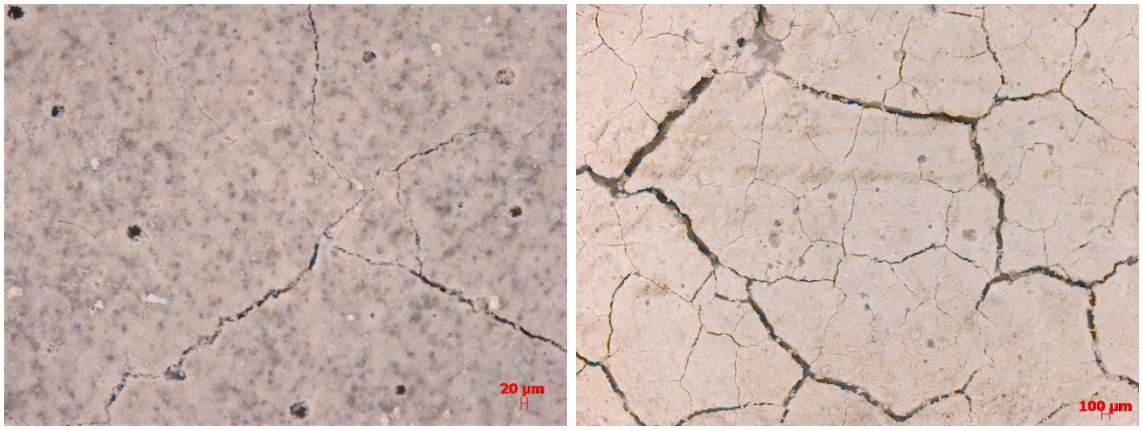


Figure 4.38 Image of C100G4 mix exposed to 600°C (left) and 800°C (right)

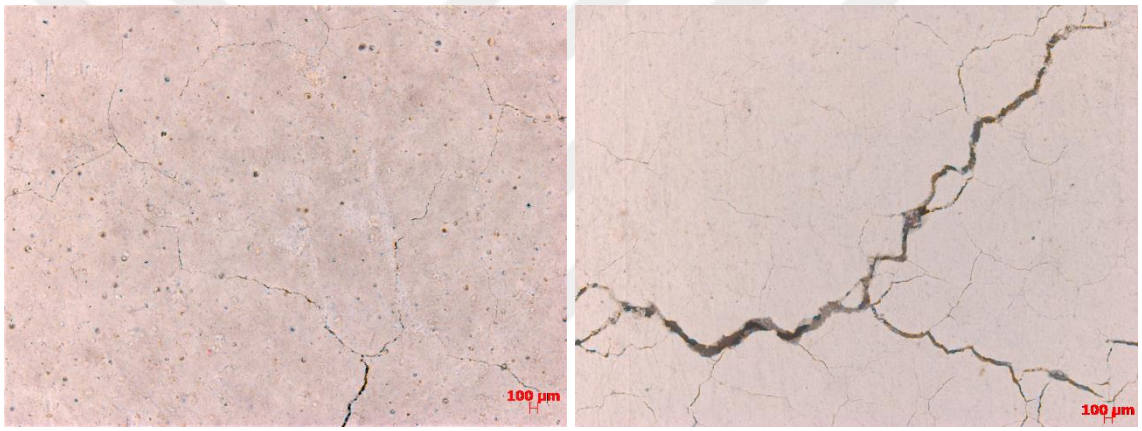


Figure 4.39 Image of C100PG4 mix exposed to 600°C (left) and 800°C (right)

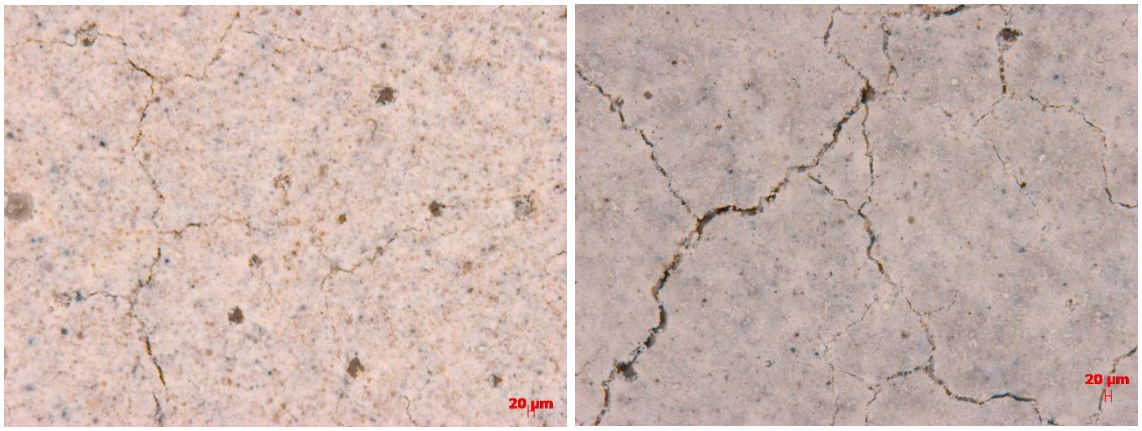


Figure 4.40 Image of F50G4 mix exposed to 600°C (left) and 800°C (right)

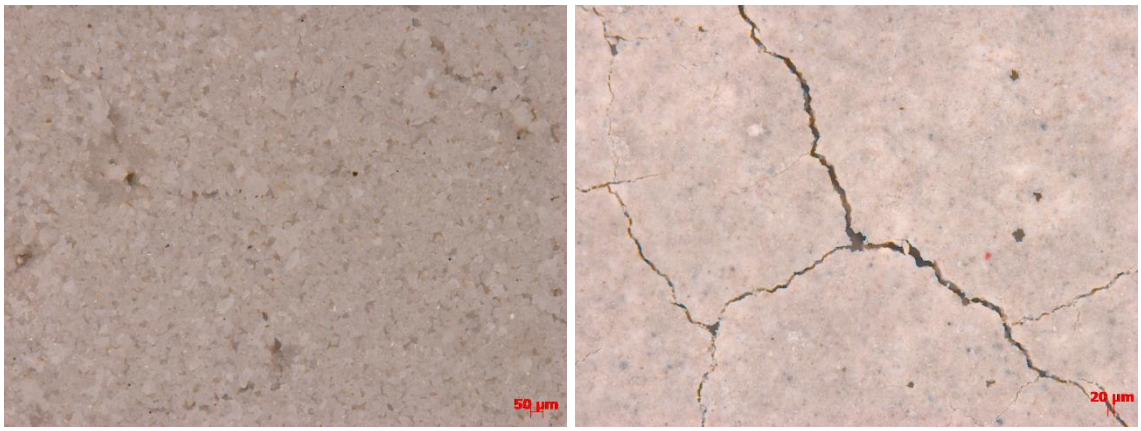


Figure 4.41 Image of F25S25G4 mix exposed to 600°C (left) and 800°C (right)

4.6 Microstructure

The microstructure of the GFRC mixes was investigated with SEM analysis on samples exposed to 800°C and their reference samples tested at ambient temperature. The SEM micrographs of the mixes presented in Figs 4.42-4.46 show that the fibers are generally pulled out and few of them were broken. The fibers are aligned in one direction as bundles in the matrix and are surrounded by hydration reaction products. The matrix penetrates intensively into the strand resulted in strong matrix-fiber bond in the C100PG3 mix as seen in Fig 4.42a. On the other hand, exposure to 800°C resulted in weakness of the bond between fiber and matrix as shown in Fig 4.42b. SEM micrographs show that the fracture mode of naturally cured mixes was generally fiber pull-out. On the contrary, the fracture mode was brittle instead of fiber pull-out in mixes exposed to 800°C. Similar behavior was observed in the C100PG4, F50G3, and F25S25G4 reference mixes tested at ambient temperature. SEM micrograph of a single fiber in the C100PG3 mix exposed to 800°C given in Fig.4.46 shows the hydration deposits on the fiber. Although the fiber surface was smooth, it is observed that the fiber suffered slight structural deformations due to the effect of high temperature.

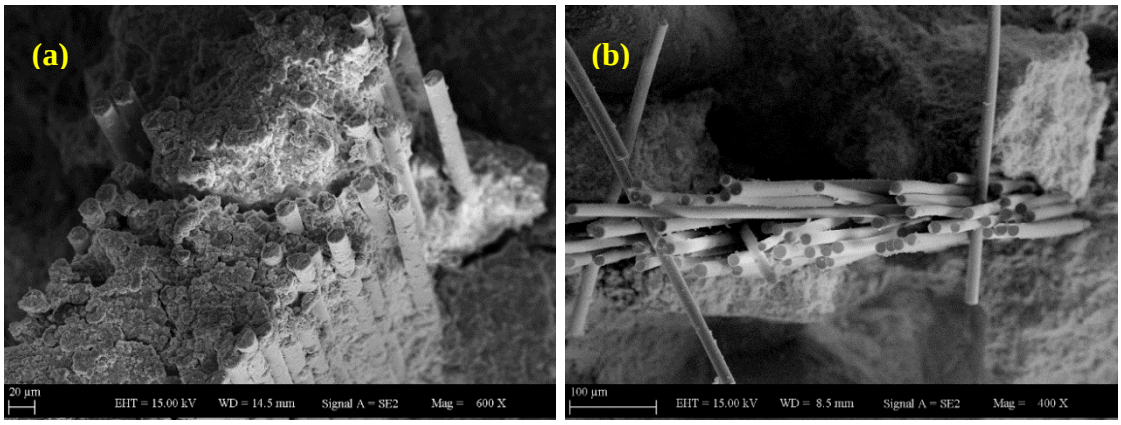


Figure 4.42 SEM image of C100PG3, (a) reference (b) exposed to 800°C

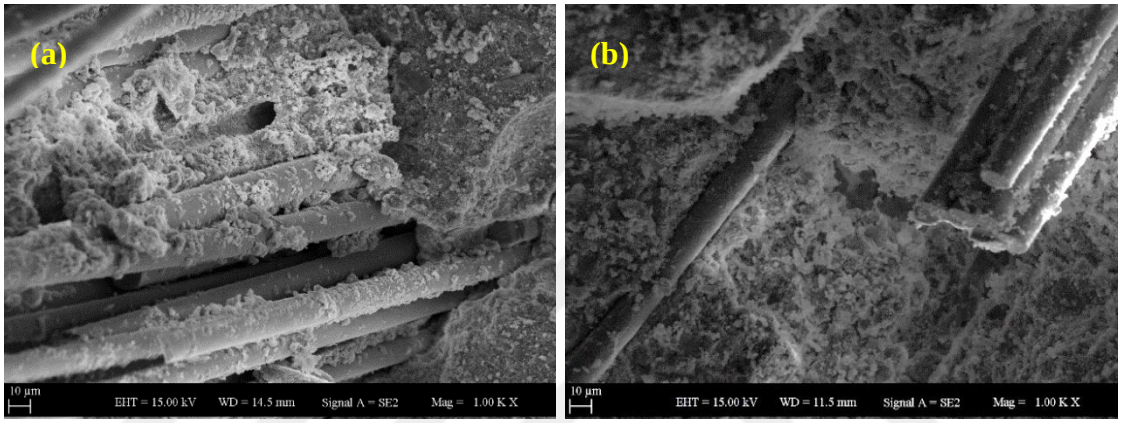


Figure 4.43 SEM image of C100PG4, (a) reference (b) exposed to 800°C

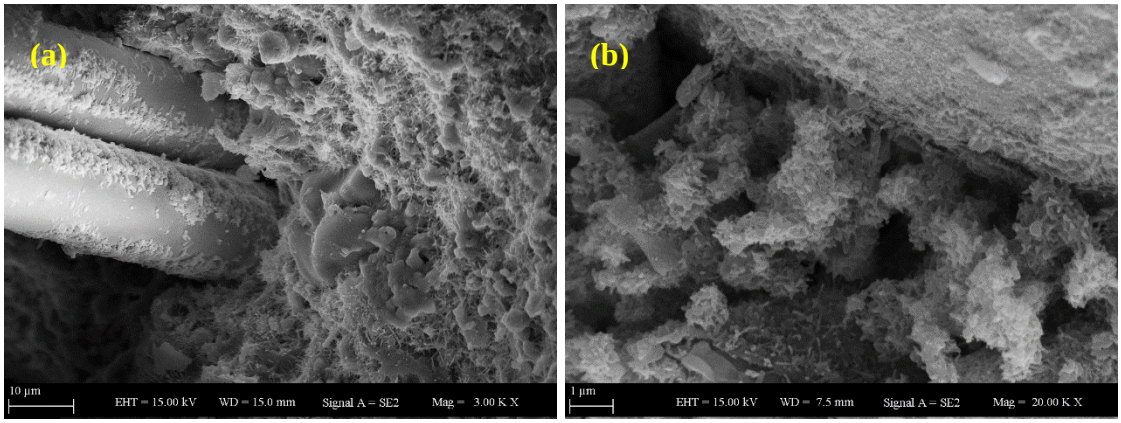


Figure 4.44 SEM image of F50G3, (a) reference (b) exposed to 800°C

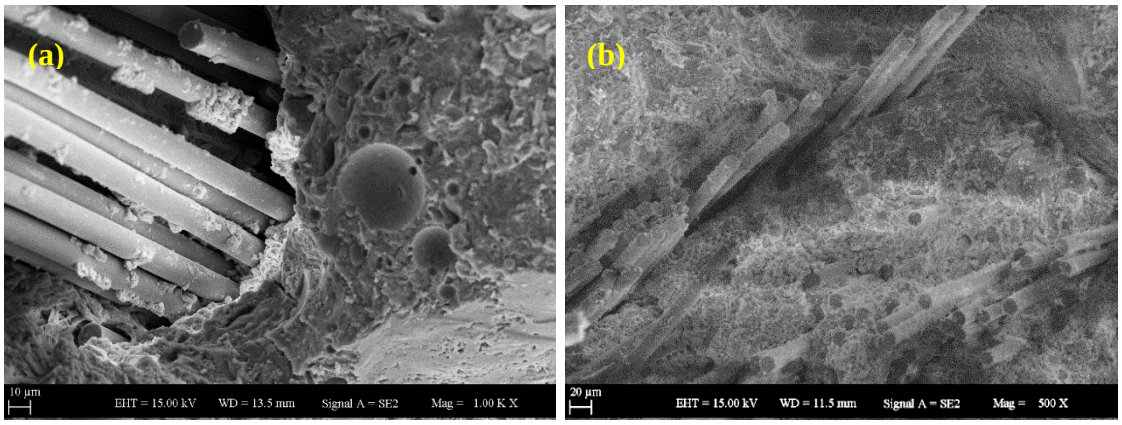


Figure 4.45 SEM image of F25S25G4, (a) reference (b) exposed to 800°C

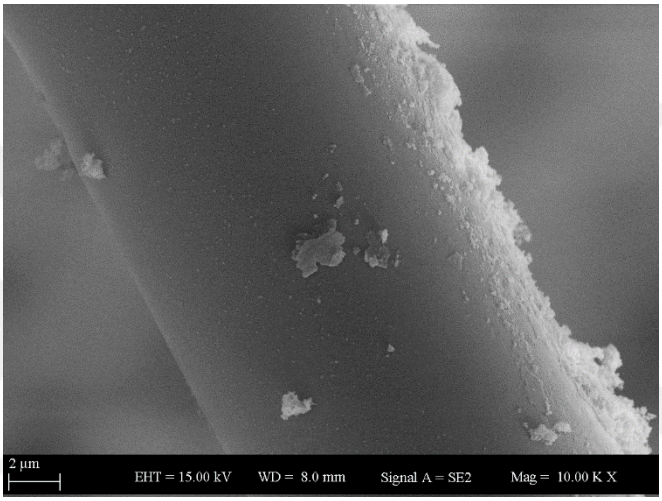


Figure 4.46 SEM image of a fiber in the C100PG3 mix exposed to 800°C

5
Conclusions and Recommendations

5.1 General Conclusions

This study investigated the effects of cement substitution with fly ash and blast furnace slag on physical, mechanical and durability properties of GFRC. Based on the physical, mechanical, and durability test results the following conclusions may be drawn:

- Substitution of cement with fly ash enhanced the workability. However, when fly ash is used in combination with blast furnace slag the workability was not significantly changed compared to the reference mix. It was found that the acrylic polymer addition significantly improved the workability. High workability was obtained in the mixes incorporating acrylic polymer and fly ash, and the need for superplasticizer was completely eliminated.
- The dry density of the mixtures increased with age. Polymer addition slightly reduced the dry density of the mixes, on the other hand substituting cement with fly ash and slag significantly reduced the density.
- Extreme dimensional variations decreased significantly with fly ash addition by more than 25% compared to the reference mixes. Although there was a decrease in dimensional changes in the mixes incorporating blast furnace slag, it was higher than the mixes with fly ash. The effect of acrylic polymer on the dimensional changes varied, while reductions were noted in the reference mixes, same trend was not observed in mixes incorporating pozzolanic materials.
- The compressive and flexural strength of the matrix mixes with pozzolanic materials were consistently lower than the reference mixes at all ages, but

the strength development of mixes with pozzolanic materials showed a significant increase with age.

- The flexural strength (σ_{MOR}) of the reference mixes were found to be higher than those containing pozzolanic materials. The highest flexural strength was found as 15.08 MPa in C100PG3 mix at 90 days. Polymer addition slightly affected the flexural strength of the mixes. The increase in fiber content, did not improve the flexural strength of reference mixtures, however the flexural strength of mixes incorporating fly ash and slag improved significantly with increasing fiber content. The deformations (ε_{LOP} and ε_{MOR}) showed no clear trend with age, while in some mixes the deformations were improved, on the other hand, in some mixes deformations were reduced or no significant change was observed. The relationship between σ_{LOP} and σ_{MOR} presented a quite well correlation representing R^2 value of 0.87.
- The plastic deflection capability of the mixes was consistently increased with acrylic polymer inclusion. The increase in fiber content also resulted in slight increase in the plastic deflection capability of all mixes.
- The toughness of the reference mixes was not improved by age, even in some cases dropped at 28 days. On the other hand, the toughness slightly improved with age in mixes incorporating fly ash and slag. The addition of acrylic polymer consistently resulted in clear increase in toughness values in all mixes. The increase in fiber content also improved the toughness of the mixtures, the exception was the reference mixtures where no significant change was observed.
- Freeze/thaw test results showed that GFRC mixtures could withstand cyclic frost action without suffering any damage, and in most cases flexural strength was significantly improved with fly ash and slag addition.
- Exposure to wet-dry cycles significantly reduced the mechanical performance of all GFRC mixes. This effect is observed to be less in the mixes incorporating pozzolanic materials and acrylic polymer.

- The flexural strength of the mixes is reduced when exposed to high temperatures of 600 and 800°C, the higher the exposed temperature resulted in higher drops in strength of all mixes. However, the substitution of cement with fly ash improved the durability against high temperature. The addition of acrylic polymer was found to increase the damage due to high temperature. The increase in the fiber content from 3 to 4% also resulted in greater strength reductions of mixes after high temperature.

5.2 Recommendations

Future work should focus on the use of different types of fibers in GFRC production. Alternative fibers durable to alkaline environment (cementitious medium) will be helpful to improve the properties of GFRC material.

Pozzolanic materials are useful in maintaining or in some cases improving the durability of the GFRC, therefore the effect different types of natural/artificial pozzolanas should be researched to reduce the amount of cement consumption. Evaluation of waste materials in GFRC will be beneficial in terms of sustainability and help reduce environmental pollution.

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Publications from the thesis

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Papers

1. B. AMED, N. KABAY, “Glass fibre reinforced precast concrete containing high content pozzolanic materials,” Sigma J. Eng. & Nat. Sci., 37, no. 2, pp. 675-686, 2019.

Projects

1. Coordinator: N. KABAY, “Yüksek oranda puzolan malzeme içeren cam elyaf takviyeli betonların mekanik ve durabilite özellikleri”, BAP-YTU, Project No: FYL-2018-3415, researcher: B. Amed.