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Glass Fibre Reinforced Concrete (GFRC)

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Abstract: In the 1940's, potential of glass as a construction material was realized and improvement continued with the addition of zirconium dioxide in 1960's for harsh alkali conditions. To enhance durability of materials, new generation of glass fibres directed to improvement process. In this way, glass fibre reinforced concrete (GFRC) was started to produce for the satisfaction of different demands. Scientific studies and tests on the GFRC have shown that the physical and mechanical properties of the GFRC change depending on the quality of the materials and the accuracy of the production methods. GFRC can be used wherever a light, strong, fire resistant, weather resistant, attractive, impermeable material is needed. As technology advances, it is possibly expected to build the whole building and complex freeform with low cost. In recent years, the effect of glass fibres in hybrid mixtures has been investigated for high-performance concrete (HPC), an emerging technology termed, which has become popular in the construction industry.

Keywords: Glass, Fibre, Reinforcement, Concrete, Properties, Application, Development

Cam Lif Takviyeli Beton

Özet: 1940'lı yıllarda camın bir yapı malzemesi olarak sahip olduğu potansiyelinin farkına varılmış ve 1960'larda zirkonyum dioksit katkısıyla iyileştirmelere devam edilmiştir. Malzemelerin kimyasal dayanımını arttırmak için yeni nesil cam lifleri, söz konusu iyileştirme sürecine dâhil edilmişlerdir. Böylece, arzu edilen beklentileri karşılamak üzere cam takviyeli beton üretimi başlamıştır. Bu grup beton üzerine gerçekleştirilen bilimsel araştırma ve testler cam lifle kuvvetlendirilmiş betonun fiziksel ve mekanik özelliklerinin kullanılan malzemelerin kalitesine ve üretim yönteminin hassasiyetine bağlı olarak değiştiğini göstermiştir. Böylesi betonlar, hafif, sağlam, ateşe ve hava koşullarına karşı dayanıklı, sızdırmaz malzeme ihtiyacı doğduğunda kullanılabilirlik arz etmektedirler. Teknoloji ilerlerken bir binanın tamamının cam takviyeli betonlarla düşük maliyetle yapımının mümkün olabileceği beklentisi de artmaktadır. Geçtiğimiz yıllarda cam elyafların hibrid karışımlardaki etkisi yüksek performanslı beton elde etmek amacıyla araştırılmaya başlanmıştır. Bu yeni teknoloji inşaat sektöründe popüler hale gelmiştir.

Anahtar kelimeler: Cam, Lif, Kuvvetlendirme, Beton, Özellikler, Uygulama, Gelişme

1. Introduction

Glass fibre reinforced concrete (GFRC) is a material that is making a significant contribution to the economics, technology and aesthetics of the construction industry worldwide for over 40 years. GFRC is one of the most versatile building materials available to architects and engineers [1–2]. Compared to traditional concrete, it has complex properties because of its special structure. Different parameters such as water–cement ratio, porosity, composite density, inter filler content, fibre content, orientation and length, type of cure influence properties and behaviour of GFRC as well as accuracy of production method [2–4]. GFRC can be produced as thin as 6 mm so their

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weight is much less than traditional pre–cast concrete products. Progressing of 3D–printing technology with glass fibre reinforced ink can build a whole building and complex architecture forms with high reliability as well as the use of premix, spray–up, hybrid methods of GFRC. Self–cleaning environmentally friendly panels for industrial construction have been contributing to the GFRC both in terms of cost and popularity. The use of glass fibre in the High Performance Concrete (HPC) class, being a class with extremely high mechanical performance, durability, workability and aesthetics, has gained momentum in recent years. The design and manufacture of GFRC products is covered by international standards, which have been developed in Europe, America, Asia and Australasia. GFRC is manufactured in over 100 countries [5–6].

2. Brief History of GFRC

Potential of glass as a construction material was realized in the 1940's. But, since the glass has very low alkali resistance to corrosion and loss of tensile strength of the glass fibres it became very difficult to be mixed with concrete which is alkaline in nature. Thus, a better glass being alkali resistant was made with the content of high level of zirconium dioxide in the mid–1960s. From this time such fibres became commercially available and new fibres and their applications were covered by patents [6–7]. In early 1980s, as evolved new generation of fibres composites throughout the matrix provided substantially increased tensile, flexural and impact strength. EN standards were developed, the quality control was increased for the best practice in production and designs supported by the International Glass Fibre Concrete Association. In the early years of new millennium rapid increase in GFRC production with the construction burst world–wide. Its growth slowed down due to the global economic crisis at one point, but the use of GFRC by major architects of the world was widespread in different areas [7–8].

3. Production of GFRC

3.1 Production Methods

There are two main production techniques of GFRC, usually preferred as spray–up and pre–mix. In the spray–up process, the mortar is produced separately from the fibres, which are mixed only at the jet of the spray gun. The glass fibre strands are cut within the spray gun to the required size, usually being between 25 mm and 40 mm and are about 4–5 % of the total mixture weight. Using matrix without fibres, a thin coat is created as thin as possible by spraying. Next layers of matrix with fibres are quickly applied to ensure integrity. After the bulk of the GFRC is built–up on it in layers the mixture is provided to toughen. Covering layer is usually 3–5 mm thick, depending on the type of surface treatment. Each pass of the spray gun deposits a layer approximately 4–6 mm in thickness, however, has to be carefully an adequate thickness in corners and complex shapes. Finally, the structure compacted with a cylindrical roller or a float so as to the impregnation of the fibres within the mortar and the removal of the air retained within the mixture. Using a depth gauge or a template, thickness of layer is checked in the specification for GFRC being the minimum (Figure 1) [9–10].

In the GFRC production method by pre–mixture and casting, cement matrix is firstly produced and pre–cut glass fibers, between 2–4 % (usually 3.5 %) weight, are then mixed. The length of the pre–cut fiber is usually 6–12 mm, however, longer fibers lead to restrict to the mixture workability. Respectively, the matrix is produced in a high–shear mixer and chopped fiber strands are incorporated in a low–speed mixing regime because of maximum workability. This facilitates their dispersion at the highest practical volume content with a minimum damage to the fibers. Production with pre–mix GFRC may involve several procedures such as injection and vibration, pressing, or shotcreting (Figure 1) [11–12].

Figure 2. Spray–up application [10].

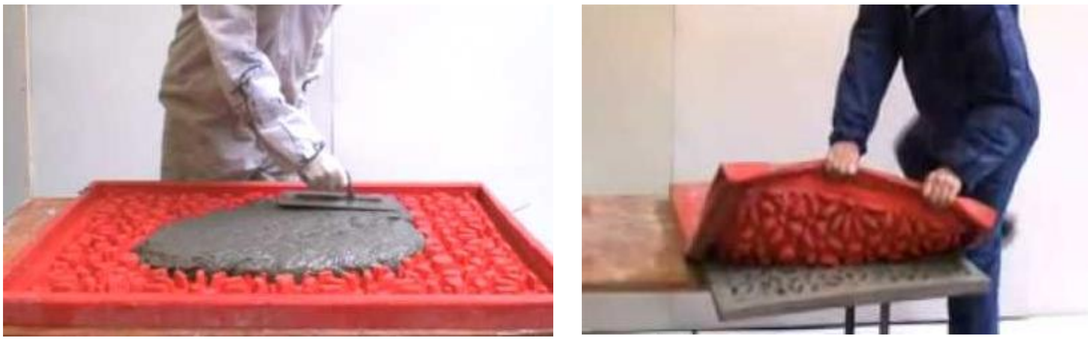

Figure 3. Pre–mixture and casting process [12].

Besides these two main production techniques there is also other production method: hybrid process. In alternative hybrid method uses hopper gun to spray the face coat. The fibre loaded backer mixture is often poured or hand packed, just like ordinary concrete. Once the thin face mixture is sprayed into the forms it is allowed to stiffen up before the backer mixture is applied so that prevents the backer mixture from being pushed through the thin face mixture. The face and backer mixtures are applied at different times because of the consistency can be different. It is always important to ensure the gross makeup similarly water/cement ratios and polymer contents should be the same to prevent curling. However, the heavy dose of fibres in the backer mixture often precludes spraying, so traditional methods is required (Figure 3) [11].

Figure 4. Spraying the face coat–face coat ready for backer mix–hand packing backer on upright [11].

3.2 Curing

Curing stage isn't essentially different from that in normal concrete technology. Moreover, the GFRC product is much more sensitive to the deleterious effects of improper water curing. Higher surface area and the low thickness of the GFRC can lead to increased drying and reductions in its strength. Because of the polymer content, long term moist curing is often unnecessary. Small amounts of acrylic polymers in the fresh mixture keep the internal moisture in and prevent its loss by evaporation. Sudden and rapid drying–out or large temperature changes must be avoided to ensure that the GFRC reaches adequate strength for the element to be safely removed from a mould. Generally, GFRC pieces are stripped the next day, mostly 16 and 24 hours after casting. Longer curing will always yield better concrete, but the general tendency is strip soon after casting [11, 13].

4. Structural Properties of GFRC

The properties of fibre reinforced cementitious materials are dependent on the structure of the composite. Therefore, in order to analyse these composites, and to predict their performance in various loading conditions, their internal structure must be characterized. The three components that must be considered are:
1. The structure of the bulk cementitious matrix,
2. The shape and distribution of the fibres,
3. The structure of the fibre–matrix interface [13].

4.1 Matrix

The bulk cementitious matrix can be divided into two types depending on the particulate filler (aggregate) which it contains: paste/mortar (cement/sand–water mix) and concrete (cement–sand–coarse aggregate–water mix). Glass fibre reinforced concrete pastes or mortars are usually applied in thin sheet which are employed mainly for cladding. In these applications the fibres act as the primary reinforcement and their content is usually in the range of 5–15 % by volume. Special production methods need to be applied for manufacturing such composites.

4.2 Fibers

There are generally two distinctly different types of fibre–reinforcing arrays: *continuous reinforcement* in the form of long fibres which are incorporated in the matrix by techniques such as filament winding or by the lay–up of layers of fibre mats; and *discrete short fibres*, usually less than 20 mm long, which are incorporated in the matrix by methods such as spraying and mixing. The reinforcing array can be further classified according to the dispersion of the fibres in the matrix, as random 2D or 3D.

The first is random, three–dimensional (3D) reinforcing. This occurs when fibres are mixed into the concrete and the concrete is poured into forms. Because of the random and 3D orientation, very few of the fibres actually are able to resist tensile loads that develop in a specific direction. This level of fibre reinforcing is very inefficient, requiring very high loads of fibres. Typically, only about 15 % of the fibres are oriented correctly.

The second level is random, two–dimensional (2D) reinforcing. This is what is in spray–up GFRC. The fibres are oriented randomly within a thin plane. As the fibres are sprayed into the forms, they lay flat, confirming to the shape of the form. Typically, 30 to 50 % of the fibres are optimally oriented [13–14].

4.3 The Structure of the Fibre–Matrix Interface

Cementitious composites are characterized by an *interfacial transition zone* in the vicinity of the reinforcing inclusion, in which the microstructure of the paste matrix is considerably different from that of the bulk paste, away from the interface. The nature and size of this transition zone depends on the type of fibre and the production technology; in some instances, it can change considerably with time. When considering the development of the microstructure in the transition zone, a bundled filament should be made and with bundled filaments only the external filaments tend to have direct access to the matrix [14–15].

5. Properties of GFRC

Different parameters such as water–cement ratio, porosity, composite density, inter filler content, fibre content, orientation and length, and type of cure influence properties and behaviour of GFRC. GFRC derives its strength from an optimal dosage of fibres and acrylic polymer. The polymer and concrete matrix serves to bind the fibres together and transfer loads from one fibre to another via shear stresses through the matrix. Density and porosity are effective on the degree of compaction [16–17].

In concrete structure, efficiency of fibres depends upon their orientation. When the fibres are aligned perpendicular to the crack openings in the direction of stress, the positive effect of fibres on the performance of GFRC is increased [18–19]. Along with that because of requiring the improvement in the long–term performance of GFRC the type of glass fibres such as E and alkali–resistant (AR) glass fibres must also be considered as well as the environmental conditions. When alkali attack considered main deterioration mechanism in E glass, there should be made an attention to seal the fibres completely from the matrix or used a very low alkali cementitious material. On the other hand, so as to improve the alkaline resistance and durability of GFRC with AR glass fibres, the main effort should be directed modifying the microstructure of the matrix in the vicinity of the glass filaments. This could be provided with controlling of the hydration process in its vicinity or changing the composition of the matrix.

The rate of ageing is a function of the type of glass fibre. New generation of AR–glass fibres are better than E glass ones. The ageing performance of the composite is also sensitive to the weathering conditions. As the aging continues in different environments, chemical attack may become significant so there is need to develop special glass fibres for better alkali resistance [20]. According to the importance of this parameters and condition affecting the features of GFRC, a review is made to demonstrate their effects on mechanical and physical properties of concrete. Some decorative materials which exhibit physical and mechanical properties of GFRC materials shown in Figures 4–5.

Figure 0. Precast GFRC table top with fire [21].

Figure 5. Design for bendable concrete (lattice pieces) [22].

5.1 Mechanical Properties of GFRC
5.1.1 Compressive Strength

The compressive strength of concrete has been increased with the addition of fibres to concrete mixes, however further addition of fibre indicated a gradual decrease in strength aspects [23–24].

5.1.2 Modulus of Elasticity

In heterogeneous and multiphase materials such as concrete, the density and the characteristics of the transition zone determine the elastic modulus behaviour of the composite. The experimental test results exhibit that the use of fibres has no important influence on the modulus of elasticity of concrete. It was reported that mostly a little reduction in the modulus of elasticity of the concrete at a low glass fibre content [25–26].

5.1.3 Stress–Strain Curve

Stress-strain behaviour is affected from different parameters such as the effect of fibre lengths, aggregate type and effect of loading rate. As it is given in Figure 6, GFRC has a significant impact on the ascending portion of the stress–strain curve and additionally, descending part of the stress–strain curve is an essential key element under compression loads [27–28].

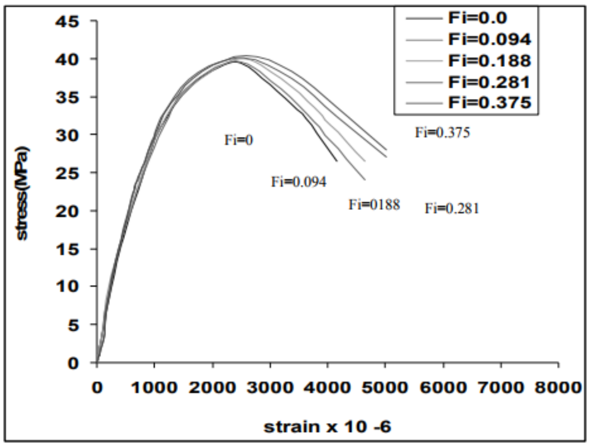

Figure 6. Stress–Strain diagram with differences at fibre ratios [28].

5.1.4 Flexural Strength

Glass fibres have an effect on the increase in the flexural strength of concrete. Figure 7 presents that an increase in the fibre content (but not much increase) resulted in an increase in the flexural strength of concrete, compared to plain concrete specimen. The fibres resist the propagation of cracks and tend to reduce the sudden failure of structure of concrete and so they lead to an increase in the load carrying capacity of concrete [29–31].

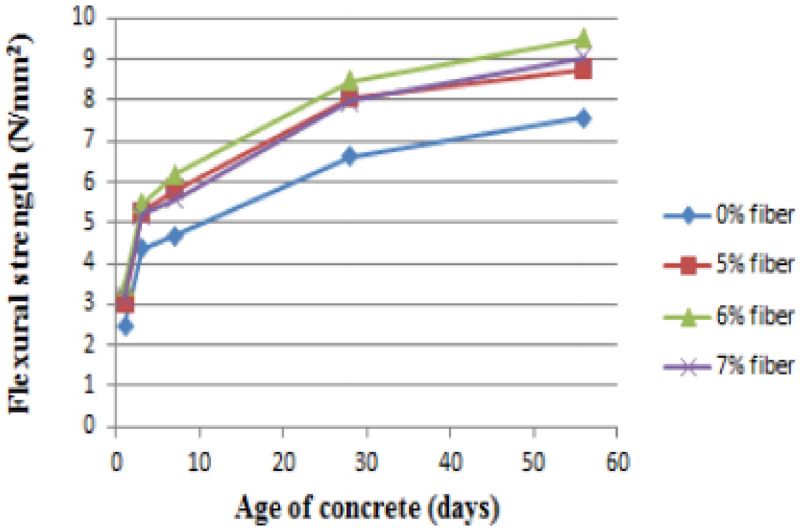

Figure 7. Variation of flexural strength with the age of concrete [31].

6. Physical Properties of GFRC
6.1 Drying shrinkage

Drying shrinkage has a significant effect on the structural and durability performance of the concrete. The mechanism of shrinkage of cementitious material is complex, but total shrinkage is principally affected by the aggregate proportion and type, and water/cement ratio, having influence on drying and causing many micro cracks propagation simultaneously. Shrinkage in concrete structures may also trigger forms of damage in concrete like as corrosion, freeze damage in this manner, seriously, shorten the service life of concretes [32–33]. Alkali–resistant glass fibres are effective in controlling restrained shrinkage cracking of concrete and they promote multiple cracking and reduce crack widths. Figures 8 and 9 indicate that an increase in the fibre content resulted in a significant reduction in the shrinkage strain of concrete, particularly from 25 to 75 days, compared to plain concrete specimen.

Figure 8. Plain (left) GFRC (right) restrained shrinkage specimens [34].

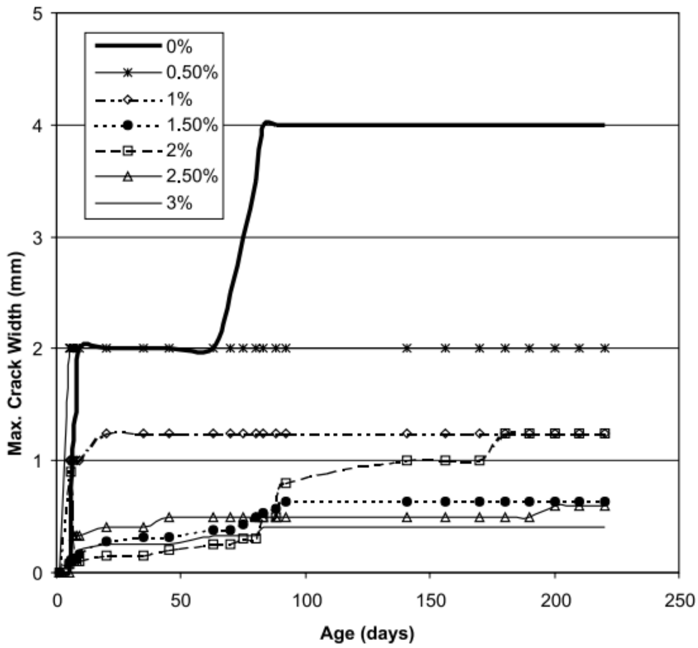

Figure 9. Restrained shrinkage test results for GFRC with different glass fibre contents [34].

6.2 Creep

Because of its poor strain capacity and low tensile strength, concrete is a brittle material and highly susceptible to cracking. These cracks can decrease the lifetime of a structure by allowing aggressive agents. Therefore, the evolution of crack openings through time is important for the durability of concrete [36]. In terms of creep and shrinkage, application technique of GFRC must be taken into account. With pneumatic spraying, glass fibre added into mortar mixture at the time of pouring and there is a significant modification of the compositions embodied in binder consumption. This can effect creep strain [37].

6.3 Porosity, Chloride Penetration Resistance and Electrical Resistivity

Concrete is a multiple–phased material, and it has lots of micro pores which can be transferred thanks to the migrating ions. Therefore, resistivity measurement is a determinative way to explore the microstructure of concrete [38]. Resistivity of concrete is influenced by many factors such as water–cement ratio, concrete composition, admixtures, curing condition, humidity. As a result, all of these impacts can trigger to increase the risk of steel rebar corrosion in the concrete [39]. This effect can be clearly seen in Figures 10–11. Along with this, chloride presence in the concrete structure can increase electrical current and the risk of corrosion [40]. Alkali resistance GFRC depicts less permeability of chloride into concrete increasing corrosion resistance. Figure 12 indicates that an increase in the fibre content resulted in a significant reduction in the chloride permeability of concrete, compared to plain concrete specimen. Thus, durability which is one of the most important aspects of the concrete, can be improved during working conditions of concrete structures [41].

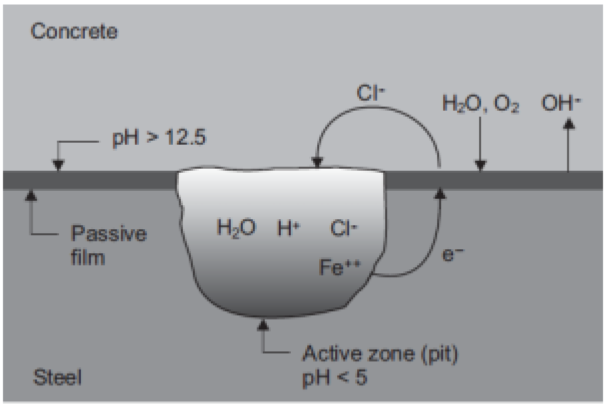

Figure 10. Chloride attack [42].

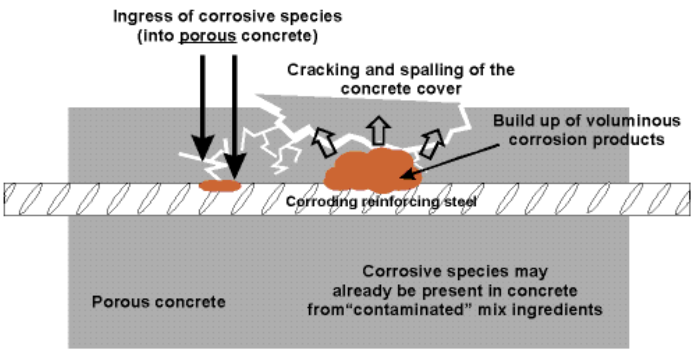

Figure 11. Cracking and spalling of the concrete cover [43].

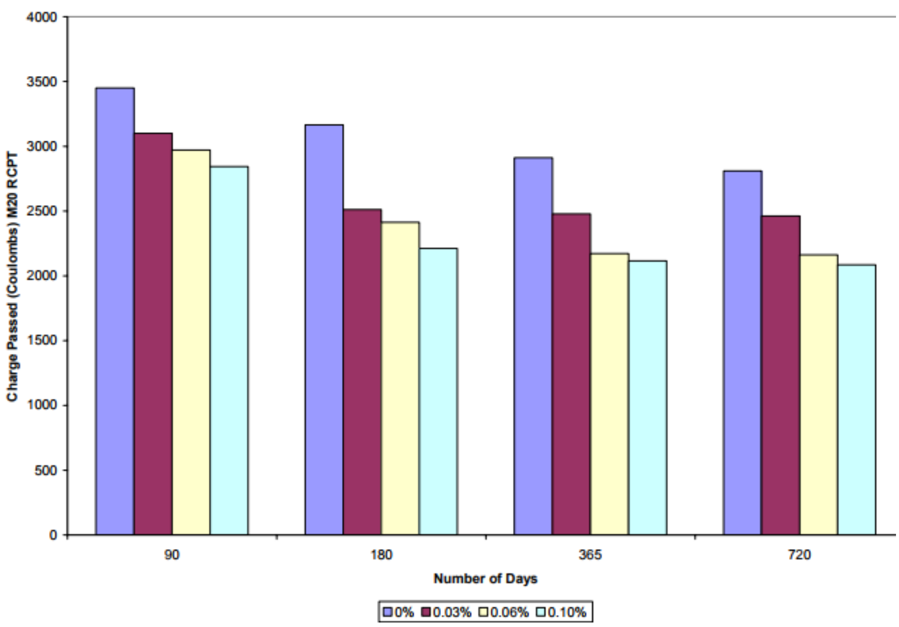

Figure 12. Rapid chloride permeability test (RCPT) (with different glass fibre) for different ages of concrete [41].

The electrical resistivity of concrete is observed to decrease with the increase in water–cement ratio. Besides, because of increasing porosity in concrete by the addition of fibers the resistivity values of fiber concretes are found lower than control concrete one [44].

Fibers can play strong positive result by holding the matrix together even if it is completely dehydrated process which triggered possibility of explosion. Addition of polymer materials to GFRC will affect the fire performance properties [16].

7. Applications and Latest Developments of GFRC

Compared to traditional concrete, GFRC has complex properties because of its special structure. As a result of the structural properties, it has suitable moulding, strong and durable structure. Moreover, because of being fast to install and easy to handle and transport, it provides low cost. It disperses or absorbs sound and it is environmentally friendly.

As total output of these properties, one of the key features of GFRC has been its versatility in use. GFRC is widely and reliably used in architecture (i.e. cladding, mouldings, landscaping), building (i.e. roofing, walls and windows, renovation, foundations and floors), engineering (i.e. permanent formwork, utilities, acoustics, bridges and tunnels, roads, water and drainage).

Figure 13. GFRC pipeline trench application (Courtesy of Nippon Electric Glass America Inc.) [45].

Figure 14. GFRC railroad track slabs for high speed trains (Courtesy of Beaker Corp. USA) [45].

Figure 15. GFRC panels used for heat insulation (Turkish Football Federation) [46]

The use of pre–mix, spray–up, hybrid methods of GFRC is becoming increasingly widespread and some amazing projects have been completed [47–49].

Figure 10. One of the earliest applications of GFRC produced by spray–up process (completed in 1974) [9].

Figure 17. A total of 110 000 m^2 of GFRC was used (Nanjing Youth Olympic Centre, China, completed in 2014) [9].

Complex freeform architecture is one of the most striking trends in contemporary architecture. Today, design and fabrication of such structures are based on digital technologies, which have been developed in other industries (automotive, naval, aerospace industry) [50]. 3D–printed building is a result of high–efficiency, environmentally–friendly and cost–effective building technology. With the progressing of 3D printing technology a whole building can be built with high reliability, which will doubtlessly make a change to the traditional construction industry. The building is printed using a huge printer which is programed for special dimensions and specially made high–strength glass fibre reinforced printing ink [51].

Figure 18. 3D Technology–Foster + Partners made from GFRG–GFRC and acrylic [50].

Because of mass colouring of GFRC is a demanding job, this situation calls for special choice of cement, granulates, fine minerals and pigments, so making it rather costly. Coloured impregnation products are alternative to the mass colouring of architectonic concrete. They provide the graduated decoration of concrete walls and can also ensure water repellence or stain can lead to repellent protection [52].

Figure 19. Colouring solution for GFRC [52].

In Türkiye, self–cleaning environmentally friendly panels for an industrial building for the first time in the world were developed with a unique glass fibre reinforced concrete solution. Because of the building is in the middle of a refinery (Tüpraş), self–cleaning GFRC panels are to be exposed harshest environment such as NO_x and SO_x emissions [53].

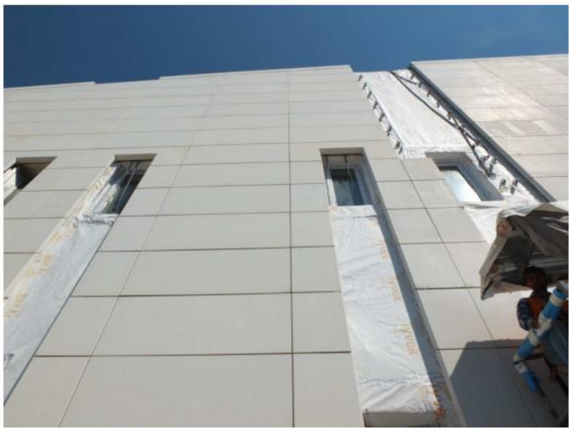

Figure 20. Façade of Tüpraş RUB [53].

High Performance Concrete (HPC) is a class of concrete characterized by extremely high mechanical performance, durability, workability and aesthetics. Due to these features some project references have increased since few years. Glass and hybrid of various fibres can be employed for self–compacting formulations [54–55].

Karasu et al. studied the use of glass in concrete reinforcement [56], the suitability for using glass and fly ash in Portland cement concrete [57], chemical durability behaviour of bulk glasses in the $SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$ (SMFMZS) system [58–59], the effects of filler glasses on mechanical properties of concrete [60], chemical dissolution mechanism of the $SrO–MgO–ZrO_2–SiO_2$ (SMZS) system glasses [61], the effect of transition metal oxide additions on the chemical durability of $SrO–MgO–ZrO_2–SiO_2$ glasses [62], $SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$ (SMFMZS) system glasses in Portland cement concrete [63], investigations on the alkali durability of the SMFMZS ($SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$) system glass fibres [64], characterization of commercially available alkali resistant glass fibre for concrete reinforcement and chemical durability comparison with $SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$ (SMFMZS) system glasses [65], electron microscopy observations on the microstructural evolution of glass fibre reinforced concrete (GFRC) materials [66–67], the use of the SMFMZS ($SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$) system glass fibres in concrete reinforcement [68], novel glass compositions for concrete reinforcement [69], investigation on fibre production attempts from the borosilicate and SMFMZS ($SrO–MgO–Fe_2O_3–Mn_2O_3–ZrO_2–SiO_2$) glass system [70], mechanical properties–microstructure relationship in high alkali resistant SMZS ($SrO–MgO–ZrO_2–SiO_2$) system glass fibre reinforced concrete [71], the effect of waste glass addition to $SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$ (SMFMZS) glasses [72], novel glass compositions for fibre drawing [73], some chemical and mechanical properties of SMZS ($SrO–MgO–ZrO_2–SiO_2$) and SMFMZS ($SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$) system glass fibres reinforced concrete (GFRC) materials [74], mechanical properties of SMFMZS ($SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$) system glass fibre reinforced concrete (GFRC) materials [75], investigations on reinforcing concrete (GFRC) materials with SMFMZS ($SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$) system glass fibres [76], the usage of high alkali resistance $SrO–Mn_2O_3–Fe_2O_3–MgO–ZrO_2–SiO_2$ (SMFMZS) system glass fibres in cement structure and their characterization [77].

Reis and Ferreira reported the assessment of fracture properties of epoxy polymer concrete reinforced with short carbon and glass fibre [78] and freeze–thaw and thermal degredation influence on the fracture properties of carbon and glass fibre reinforced polymer concrete [79].

Purnell and Beddows reported that durability and simulated ageing of new matrix glass fibre reinforced concrete [80]. Avci et al. made a search on mixed–mode fracture behaviour of glass fibre reinforced polymer concrete [81]. Abbasi and Hogg examined the temperature and environmental effect on glass fibre rebar: modulus strenght and interfacial bond strenght with concrete [82] and a model for predicting the properties of the constituents of a glass fibre rebar reinforced concrete beam at elevated temperature simulating a fire test [83].

El–Ragaby et al. seached for fatigue analysis of concrete bridge desk slabs reinforced with E–glass/vinyl ester FRP reinforcing bar [84]. Razaqpure et al. investigated blast loading response of reinforced concrete panels reinforced with externally bonded GFRP laminates [85].

Lee et al. conducted a research on interfacial bond strenght of glass fibre reinforced polymer bars in high–strenght concrete [86]. Tang et al. worked on bond performance of polystyrene aggregate concrete (PAC) reinforced with glass fibre–reinforced polymer (GFRP) bars [87].

Asokan et al. studied assessing the recycling potential of glass fibre reinforced plastic waste in concrete and cement composites [88]. Scheffler et al. reported the interphase modification of alkali–resistant glass fibres and carbon fibres for textile reinforced concrete I: fibre properties and durability [89] and II: water absorption and composite interphases [90]. Hao et al. conducted a seach on bond strenght of glass fiber reinforced polymer ribbed rebars in normal strenght concrete [91].

Asokan et al. worked on the improvement of mechanical properties of glass fibre reinforced plastic waste powder filled concrete [92]. Abtahi et al. made a general review on fibre–reinforced asphalt–concrete [93].

Soong et al. published a paper on the fundamental mechanisms of bonding of glass fibre reinforced polymer reinforcement to concrete [94]. Issa et al. conducted a research on the influence of fibres on fluxural behavior and ductility of concrete beams reinforced with GFRP rebars [95]. Tysmans, et al. established form finding methodology for forced–modelled anticlastic shells in glass fibre textile reinforced cement composites [96]. Enfedaque et al. worked on the failure and impact behavior of facede panels made of glass fibre reinforced cement (GRC) [97].

Borhan investigated the properties of glass concrete reinforced with short basalt fibre [98]. Choi et al. studied bond strenght of glass fibre–reinforced polymer bars in unconfined concrete [99]. Barhum and Mechtcherine reported the effect of short, dispersed glass and carbon fibres on the behaviour of textile–reinforced concrete under tensile loading [100]. Emiroğlu et al. made ANFIS and statistical based approach to prediction the peak pressure load of concrete pipes including glass fiber [101]. Zheng et al. have made an investigation of structural behaviours of laterally restrained GFRP reinforced concrete slabs [102]. Limbachiya et al. examined performance of granulated foam glass concrete [103]. Nunes and Reiss carried out a research on the estimation of crack–tip–opening displacement and crack extention of glass fiber reinforced polymer mortars using digital image correlation method [104]. Li et al. stuided the flexural behavior of GFRP–reinforced concrete encased steel composite beams [105].

Sayyar et al. conducted a study on the low–cost glass fiber composites with enhanced alkali resistance tailored towards concrete reinforcement [106]. Job has writen a paper on the history and proggress of recycling glass fibre reinforced composites–history and proggress [107]. Saribiyik et al. reported the effects of waste glass powder usage on polymer concrete properties [108]. Shi–Cong and Chi–Sun researched a novel polymer concrete made with recycled glass aggregates, fly ash and metakaolin [109]. Carvelli et al. investigated high temperature effects on concrete members reinforced with GFRP rebars [110]. Robert and Benmokrane carried on working on combined effects of saline solution and moist concrete on long–term durability of GFRP reinforcing bars [111].

Tassew and Lubell reported the mechanical properties of glass fibre reinforced ceramic concrete [112]. Bathia et al. have given valuable results of sustainable fiber reinforced concrete for repair applications [113]. Pastor et al. searched for glass reinforced concrete panels containing recylcled tyres: evaluation of the acustic properties for their use as sound barriers [114]. Criado et al. carried out a work on the effect of recycled glass fiber on the corrosion behavior of reinforced mortar [115]. Bhoopathi et al. examined the fabrication and property evaluation of banana–hemp–glass fiber reinforced composites [116]. Wang et al. have given their experimental results on the flexural properties of epoxy syntactic foams reinforced by fiberglass mesh and/or short glass fiber [117]. Nigro et al. presented guidelines for flexural resistance of FRP reinforced concrete slabs and beams in fire [118]. García et al. worked on mechanical recycling of GFRP waste as short–fiber reinforcement in microconcrete [119].

Henriksen et al. made an innovative approach to manufacture thin–walled glass fibre reinforced concrete for tomorrow’s architectural buildings envelopes with complex geometries [120]. Maranan et al. evaluated the fluxural strenght and serviceabality of geopolymer concrete beams reinforced with glass–fibre–reinforced polymer (GFRP) bars [121]. Pehlivanlı et al. studied the mechanical and microstructural features of autoclaved eareted concrete reinforced with autoclaved polypropylene, carbon, basalt and glass fiber [122]. Ge et al. conducted a research on glass fiber reinforced asphalt membrane for interlayer bonding between asphalt overlay and concrete pavement [123]. Jarek and Kubik made an examination on the glass fiber reinforced polymer composite rods in terms of the application for concrete reinforcement [124]. Schmitt et al. searched for thermo–mechanical loading of GFRP reinforced thin concrete panels [125]. Miotto and Dias discussed the structural efficiency of full–scale timber–concrete composite beams strenghtened with fiberglass reinforced polymer [126]. Kushartomoa et al. examined the mechanical behavior of reactive powder concrete with glass powder substitute [127]. Garcia–Espinel et al. made a publication on the effects of sea water environment on glass fiber reinforced plastic materials used for marine civil engineering constructions [128]. Ferreira et al. searched for shear strain influence in the service response of FRP reinforced concrete beams [129]. Pagliolico et al. made a preliminary study on light transmittance properties of translucent concrete panels with coarse waste glass inclusions [130]. Neagoe et al. made an experimental study of GFRP–concrete hybrid bems with low degree of shear connection [131]. Das et al. gave a report on the flexural fracture response of a novel iron carbonate matrix–glass fibre composite and its comparison to Portland cement–based composites [132]. Kizilkanat et al. conducted an experimental study on the mechanical properties and fracture behavior of basalt and glass fibre reinforced concrete [133].

Mastali et al. finished a study on the impact resistance and mechanical properties of reinforced self–compacting concrete with recycled glass fibre reinforced polymers [134]. Henriksen et al. showed a new method to advance complex geometry thin–walled glass fibre reinforced concrete element [135]. Man et al. exhibited the expansion behavior of self–stressing concrete confined by glass–fiber composite meshes [136]. Khan and Ali used the glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks [137]. Arslan investigated the effects of basalt and glass chopped fibers addition on fracture energy and mechanical propertiers of ordinary concrete [138]. Zhao et al. searched for the effect of fiber types on creep behavior of concrete [139]. Rudnov et al. wrote a paper on the properties and design characteristics of the fiber concrete [140]. Wroblewski et al. outlined the durability of bond between concrete beams and FRP composites made of flax and glass fibers [141]. Vaitkevičius et al. studied advanced mechanical properties and frost damage resistance of ultra–high performance fibre reinforced concrete [142]. Aliabdo et al. tried to utilize the waste glass powder in the production of cement and concrete [143]. El–Nemr et al. carried out a research on bond–dependent coefficient of glass– and carbon–FRP bars in normal– and high–strenght concretes [144]. Bouziadi et al. published a paper on the effects of fibres on the shrinkage of high–strenght concrete under various curing temperatures [145]. Yan and Lin examined bond behavior of GFRP bar–concrete interface and gave damage evolution assesment and FE simulation implementations [146]. Gao et al. have given knowledge about the behavior of glass and carbon FRP tube encased recycled aggregate concrete with recycled clay brick aggregate [147]. Ateş searched for mechanical properties of sandy soils reinforced with cement and randomly distributed glass fibers (GRC) [148]. Yan et al. made a review on bond mechanism and bond strenght of GFRP bars to concrete [149]. Huo et al. made an experimental study on dynamic behavior GFRP–to–concrete interface [150]. Fursa et al. used the electric response to mechanical impact for evaluating the durability of the GFRP–concrete bond during the freze–thaw process [151]. Wu et al. searched for improved bond behavior between GFRP rebar and concrete using calcium sulfoaluminate [152]. Nobili published a paper on the durability assessment of impregnated glass fabric reinforced cementitious matrix (GFRCM) composites in the alkaline and saline environment [153]. Yan and Lin established a new strategy for anchorage reliability assessment of GFRP bars to concrete using hybrid atrificial neural network with genetic algorithm [154].

Dehghan et al. studied recycled glass fibre reinforced polymer additions to Portland cement concrete [155]. Alberti et al. carried out a work on fibre reinforced concrete with a combination of polyolefin and steel–hooked fibre [156]. Amin et al. made materials characterisation of macro synthetic fibre reinforced concrete [157]. Dal Lago et al. conducted full–scale testing and numerical analysis of a precast fibre reinforced self–compacting concrete slab pre–stressed with basalt fibre reinforced polymer bars [158]. Hamad aimed to find the size and shape effect of specimen on the compressive strenght of HPLWFC reinforced with glass fibres [159].

Ahmad et al. reported an experimental study on the properties of normal concrete, self–compacting concrete and glass fibre–reinforced self–compacting concrete [160]. Panda et al. examined anisotropic mechanical performance of 3D printed fibre reinforced sustainable conctruction material [161]. Kodur and Bhatt made an numerical approach for modeling response of fibre reinforced polymer strenghtened concrete slabs exposed to fire [162]. Lee et al. examined the flexural capacity of fibre reinforced concrete with a consideration of concrete strength and fiber content [163]. Sivakumar et al. conducted an experimental study on combined effects of glass fibre and metakaolin on the rheological, mechanical and durability properties of self–compacting concrete [164]. Sathanandam et al. searched for low carbon building: experimental insight on the use of fly ash and glass fibre for making geopolymer concrete [165]. Fathi et al. published a paper on the simultaneous effect of fiber and glass on the mechanical properties of self–compacting concrete [166]. Zia and Ali studied the behavior of fibre reinforced concrete for controlling the rate of cracking in canal–lining [167]. Xiaochun et al. concentrated themselves on the corrosion mechanism and and performance analysis for the applicability of alkaline–resistant glass fibre in cement mortar of road pavement [168]. Mohajerani et al. made a review on practical recycling applications of crushed waste glass in conctruction materials [169]. Enfedaque et al. have given numerical simulation of the fracture behaviour of glass fiber reinforced cement [170]. Barris et al. carried out an experimental study on crack width and crack spacing glass–FRP reinforced concrete beams [171]. Pakravan et al. published a review paper on hybrid short fibre reinforcement system in concrete [172]. Yan et al. reported an experimental study on bond durability of glass fiber reinforced polymer bars in concrete exposed to harsh environmental agents: freze–thaw cycles alkaline–saline solution [173]. Leone et al. investigated tensile properties and bond performance on masonry substrate for glass fabric reinforced cementitious matrix [174]. Gemi et al. made an experimental study on compressive behavior and failure analysis of composite concrete confined by glass/epoxy ± 55° filament wound pipes [175]. Valvona et al. examined effective seismic strenghtening and monitoring of a masonry vault by using glass fibre reinforced cementitious matrix with embedded fiber Bragg grating sensors [176]. Krayushkina et al. made an investigation of fiber concrete for road and bridge building [177]. Benmokrane et al. have given a laboratory assessment and durability performance of vnyl–ester, polyester, and epoxy glass–FRP bars for concrete structures [178]. Hambach and Volkmer reported the properties of 3D–printed fiber–reinforced Portland cement paste [179]. Riad et al. have indicated the effect of discrete glass fibers on the behavior of R.C. beams exposed to fire [180]. Youssef and Hadi dealed with axial load–bending moment diagrams of GFRP reinforced columns and GFRP encased square columns [181]. Bazli et al. conducted experiments and studied probabilistic models of bond strenght between GFRP bar and different types of concrete under aggressive environments [182].

Garciá et al. searched for the fabrication, optimization and durability evaluation of self cleaning and depolluting glass reinforced concrete panels [183]. Guo et al. studied on reduced alkali–silica reaction damage in recycled glass mortar samples with supplementary cementitious materials [184].

8. Conclusions

GFRC is one of the most versatile building materials available to architects and engineers. It has contributed significantly to the economics, technology and aesthetics of the construction industry. In line with this importance, a comprehensive review that was investigated widespread methods of production of GFRC and compatibility of developing technology was hereby aimed in understanding on the mechanical and physical properties of GFRC.

In general, the addition of glass fibre results in a higher compressive strength, but excessive amount of fibre causes a reduction in the strength due to reduced workability. There is no significant improvement in the modulus of elasticity of the concrete with the addition of fibres a low volume fraction. Glass fibres have positive effect on stress–strain curve of GFRC and flexural strength, because of the increase in the aspect ratio of fibres resulting in an increase pull-out and energy absorption of the GFRC.

Generally, GFRC's service life is higher than traditional concrete due to controlling of micro cracks propagation, corrosion (especially AR–glass fibre) and less permeability. GFRC is lightweight and is about 50–70 % lighter than traditional concrete. However, it is difficult to self–mix (requirement of special material). Its cost is higher than that of traditional concrete due to the fiberglass, addition of additives and acrylic co–polymer, but developing technology can substantially change this comparison.

GFRC is widely and reliably used in architecture, building, engineering applications. Moreover, complex forms, decorative materials and a whole building can be produced with the aid of digital technologies. GFRC is also a very important resource which includes self–cleaning environmental friendly panels, easily dyeable surfaces, and high performance concrete applications.
Consequently, there is lots of GFRC applications in practice, but with very little research to support it. In response to this expanding use requirement in practice, advanced GFRC research can be performed so as to improve its properties further.

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