Properties of thin wall cement composites reinforced with AR glass, carbon and PVA fibres

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Abstract. Thin wall cement composites find a wide range of special applications for making light weight façade exterior wall and urban decorative elements, as well as a part of load bearing constructions. AR glass fibre is the most popular reinforcing material for producing glass fibre reinforced concrete (GRC). Possibilities for use alternative Carbon and PVA fibres are analysed in this work. The study is focused on investigation of technological and mechanical properties of thin wall (15 mm) cement composite plates reinforced by tree types of fibres.

1. Introduction
Conventional manufacturing innovations offer wide range of production methods for fibre reinforced concrete, such as 3D- Molding and 3D Printing. Using these methods, different unique products can be made from fibre reinforced cementitious composites- from flower and trash pots to stunning exterior precast concrete wall panels [1-4].

In many GRC manufacturing processes, self- consolidating concrete (SCC) is preferred due to good workability and final product quality. This is very important in case of thin mold casting process, when concrete mix must fill narrow spaces- 10 mm to 20 mm, depending on product thickness. Studies showed, that 12 mm long glass fibres are a good choice for self-consolidating fibre reinforced premix, because most of the filaments still stay in bundles even after very intense mixing speeds after 1 minute up to 1000 RPM.

The interest of modern researchers and manufactures of fiber reinforced decorative elements started in UK. First known application of glass fibres in construction was The Credit Lyonnais Building, built in London in 1956 (Figure 1). Even though glass fibres used for reinforcement of exterior panels were from regular glass, this architectural masterpiece is still standing today and demonstrating all- round performance capability of the product [5].

Typical E- glass (fiberglass) was invented in 1932 by R.G. Slayter which is still widely used for fiber- reinforced polymer composites. Fibre glass chemical corrosion in alkali environment is well understood and investigated process and for this reason, E- Glass should never be used in cementitious composites [6-9]. First generation alkali resistant (AR) glass was invented in 1970’s and it’s chemical resistance to hydroxyl ion attack drastically improved [10]. Nevertheless, GRC composite loses significant portion of it’s initial strength under natural weathering conditions due to complex hydration processes which induce micro surface flaws on the surface of glass filaments and increases brittle
behavior of the composite. For this reason, alternative fibres for GRC such as carbon or PVA (Polyvinyl Alcohol) should be also investigated.

![Figure 1](https://twitter.com/royalfineart/status/770968500852649984)

**Figure 1.** The Credit Lyonnais Building, built in London in 1956, exterior panels made from early developments of glass fibre reinforced concrete (GRC).

One research showed, that carbon fibres significantly reduced concrete slump and decreased compressive strength by up to 58%. On the other hand, tensile splitting strength increased by 17% and flexural fracture energy increased by 41%, when 0,25% of fibres were added from mass of cement. Scanning electron micrographs of the fractured concrete specimens revealed that carbon fibres were distributed in SCC without any fibre clumping or fibre balling [11].

In another research it was found that CFRSCC mixtures with carbon fibres content up to 0.75% satisfactorily passed the requirements of SCC. Slump flow time was increased with the increase in carbon fibres content because the inclusion of fibres slowed the flow of CFRSCC mixture by making it more viscous [12].

PVA fibres has high contribution to post- peak flexural behavior with single-crack strain–hardening response. Studies show that short polyvinyl alcohol (PVA) fibres can significantly improve mechanical characteristics as well as long term behaviour of cement-based composites [13,14]. Flexural displacement (ductility) at ultimate load increased by 50-150 times and ultimate flexural strength by 50-250% than plain concrete [15,16].

2. Materials and Methods
Rapid hardening Portland cement CEM I 52,5R was used as a binder. Quartz sand was chosen as matrix filler (Figure 1). Polycarboxilic ether- based superplasticizer was used as a water reducing agent. For matrix reinforcement, three different fibres were used- AR glass, carbon and polyvinyl alcohol (PVA) with the same length- 12mm. Properties of fibres are compared in Table 1.

| Properties             | AR Glass fibres | Carbon fibres | PVA fibres |
|------------------------|-----------------|---------------|------------|
| Tensile strength, MPa  | 1400            | 3000          | 800        |
| Modulus of elasticity, GPa | 74             | 350           | 40         |
| Thermal resistance, °C | -50…+350        | 300           | 100        |
| Density, kg/m³         | 2500            | 1570          | 1300       |
| Fibre length, mm       | 12              | 12            | 12         |
| Filament diameter, μm  | 18              | 5             | 660        |
| Filaments per bundle, pcs | 200           | 3000          | 1          |
Mix compositions were designed according EN 15191 and common self-compacting GRC practice and are given in Table 2. Binder to filler ratio was 1:1, water-cement ratio (W/C) – 0.36, superplasticizer – 1.1% from mass of cement. Fiber content is calculated by mass from the whole weight of the matrix. Mass proportions of PVA and glass fibres were calculated so that volumetric concentrations of fibres were the similar (compositions GF and PV). Significantly lower contents of carbon were chosen due to high negative impact to mix workability, because high shear mixer with up to 800 rpm was used for all tested compositions.

**Table 2. Compositions of concrete mixtures (proportions by mass).**

| Mix Id. | CEM I 52.5R | PCE* | W/C  | Quartz sand | Glass fibres | Carbon fibres | PVA fibres |
|---------|-------------|------|------|-------------|--------------|---------------|------------|
| REF     | 1           | 1.1% | 0.36 | 1           | 0            | 0             | 0          |
| GF      | 1           | 1.1% | 0.36 | 1           | 2.9%         | 0             | 0          |
| C1      | 1           | 1.1% | 0.36 | 1           | 0            | 0.7%          | 0          |
| C2      | 1           | 1.1% | 0.36 | 1           | 0            | 0.2%          | 0          |
| PV      | 1           | 1.1% | 0.36 | 1           | 0            | 0             | 1.5%       |

*Polycarboxilate ether based superplasticiser

Workability of fresh concrete was tested according EN 1170-1. Compressive strength was tested according EN 196-1 with prisms 40x40x160, after 28 days curing in natural conditions. Fracture characteristics was determined according EN 1170-4, by casting concrete boards 525x525x15mm and cutting them into specimen plates 262x50x15 mm, which were oriented in perpendicular direction. Flectural test was carried out in accordance with 4-point loading scheme. Distance between support 224 mm and distance between loading points 75 mm was provided. Plates were tested after 28 days and bending curves plotted.

**Figure 2.** Cumulative curve of quartz sand filler.

**Figure 3.** Glass fibres (on the left) and PVA (on the right).
3. Results and Discussion

3.1. Workability

Best mix workability was achieved with PVA and glass fibres while the use of carbon fibres had significant impact on the mix workability. Considerable decreasing of mix slump may be due to a high dispersity and specific distribution of carbon fibres in cement matrix. Slump test results are given in Table 3 and Figure 3.

Glass fibres consist of 200 individual filaments, which are kept in a bundle due to high electrostatic forces between them. During high shear mixing process most of the glass filaments do not disintegrate from the bundles (Figure 4) and there was no significant slump difference between reference composition REF without fibres and GF with glass fibre. Carbon fibres showed very weak bond between the filaments and completely disintegrating from the bundles, resulting in severe slump modification. Even with as little as 0.2% of carbon fibre, concrete mix by no means can be considered as self-compacting and requires intense vibration to cast the moulds.

On the other hand, 660 μm diameter PVA fibres showed almost no impact to the mix workability, very similar to REF composition without fibres. This fact makes PVA good alternative matrix reinforcement, when mix workability is discussed.

| Mix Id. | Slump cm |
|---------|----------|
| REF     | 19       |
| GF      | 18       |
| C1      | 0        |
| C2      | 0        |
| PV      | 18       |

Table 3. Slump test results.

![Slump test photos](image1.png)

Figure 4. Slump test photos a) Reference specimen REF, without fibres, b) GF with glass fibre, c) C1 with carbon fibres.

![SEM micrograph](image2.png)

Figure 5. SEM micrograph with glass fibre bundle in hardened matrix.
3.2. Flexural resistance

Flexural tests with thin plates 15x50x262mm were done and load-deflection curves made to describe fracture characteristic with different types of fibres. Results showed that glass and PVA fibres significantly increase ductility of the matrix.

Flexural strength values at different deflections are given in Table 4 and flexural resistance curves in Figure 5. Unreinforced reference samples REF showed usual brittle behaviour with average flexural capacity 6.8MPa. Carbon significantly increased flexural capacity of the matrix up to 10.7 MPa. But fracture behaviour of carbon reinforced matrix was brittle, and specimens ruptured below 2 mm deflection. Glass fibre specimens ruptured below 5 mm deflection and maintained 40% of maximum flexural capacity at 3 mm deflection. PVA fibred showed highest matrix ductility with 62% of maximum capacity at 6 mm deflection and 84% at 3 mm.

Table 4. Flexural stress at 0 mm, 3 mm and 6 mm stroke (plates 15x50x262, 28 days).

| Composition | Flexural stress after 28 days, MPa |
|-------------|-----------------------------------|
|             | at 0.25 mm deflection | at 3 mm deflection | at 6 mm deflection |
| REF         | 6.8                  | 0                   | 0                   |
| GF          | 10.9                 | 4.3                 | 0                   |
| C1          | 9.1                  | 0                   | 0                   |
| C2          | 10.7                 | 0                   | 0                   |
| PV          | 8.9                  | 7.5                 | 5.5                 |
3.3. Concrete densities and water absorption

Hardened concrete densities are given in Figure 6 and water absorption in Figure 7. Results show, that reference sample REF had densest matrix and lowest water absorption. Added glass and carbon fibres decreased matrix density by 3.4%, PVA- by 1.4%. Added glass fibres increased matrix water absorption by 10%, carbon fibres- by 1.4%, PVA fibres did not have any significant influence.

4. Conclusions

Results of this study demonstrate possibility to use polyvinyl alcohol (PVA) fibres as alternative to AR glass in ductile GRC composites. Introduction of carbon fibre to cementitious matrix significantly increases flexural capacity, but the composite still ruptures in a brittle behavior. Similar volume of PVA fibres as AR glass in the same Portland cement matrix significantly increased composite ductility.
Flexural capacity with PVA was by 18% lower than typical glass fibre reinforced composite (GRC). Workability tests according to EN 1170-1 slump method showed, that PVA fibres has minor impact on slump, when compared with reference matrix sample without fibres. On the other hand, carbon filaments easily disintegrate from fibre bundles during high shear mixing process and mix workability goes far beyond any self-compacting limits and needs intense vibration to cast the molds. Glass fibres had the highest effect on matrix water absorption, increasing it by 10% from the reference sample.

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