Effect of Aggregates on the Technological and Mechanical Properties of Glass and Basalt Fibres Reinforced Concrete

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Abstract. Reinforcement of high performance concrete (HPC) with glass and basalt fibres is becoming more widely used due to their high mechanical properties, sustainable manufacturing process and wide range of application in architectural and urban design. Properties of HPC composites are mainly determined by matrix composition, fibre type, volume and distribution in the concrete matrix. Granulometry and shape of aggregates has a major impact on the technological properties of concrete mix, such as water bleeding and slump size. Current study is focused on investigation of HPC reinforced by glass and basalt fibres with aggregates of different types. Quartz sand and crushed granite were used as aggregates. Two matrix compositions were used, both having proportion 1:1 of ordinary Portland cement (OPC) and total amount of aggregate. In the first case, the whole aggregate was quartz sand, and for the second it was 50% quartz sand and 50% crushed granite. For matrix reinforcement, 3% of alkali resistant glass fibres and 1.5% chopped basalt from total weight of dry materials were used. 1% from cement mass of polycarboxylate ether-based superplasticizer was used to increase workability of concrete mix. The consistency of mixtures decreased, but flexural strength increased approximately by 13% when 50% of quartz sand was replaced with crushed granite for concrete with both types of fibres.

1. Introduction

Glass fibre reinforced concrete (GRC) offers designers and architects a wide range of unique applications for making outstanding façade and urban elements from small trash containers to complex 3-D shape exterior wall elements [1,2]. Developers from USA also report successful GRC implementation in restoration of historic buildings [3]. Danish innovations, such as 3D adaptive moulds opens possibilities to create complex curvilinear moulds for GRC or other concretes [4]. Chinese are already printing houses since year 2002 with technology based on glass fibre reinforced gypsum [5]. Development of GRC industry in Japan was a long battle with tough climate and hard weathering conditions for any type of concrete [6]. This is probably one of the reasons why Japan now is a leading global manufacturer of alkali resistant glass fibres.

Self-compacting concrete (SCC) was developed in Japan in 1989 and has been widely used around the world ever since. Main advantages of SCC are increased efficiency of the concreting process, better quality of concrete surfaces and more flexibility in complex moulding. From technological perspective, glass reinforced concrete (GRC) addresses same workability issues as regular self-
compacting concrete, which are water bleeding segregation and flowability. Due to a very high volume of fibres in the mix, GRC can be considered as one of the most difficult mortars to flow.

Typical GRC composition consists of quartz sand, ordinary Portland cement (OPC), superplasticizer, alkali resistant glass fibres and water. Sand and cement are added in equal proportions and blended in high shear mixer with w/c ratio between 0.32-0.40 when modern superplasticizers such as polycarboxylate ethers (PCEs) are used. Finally, alkali resistant glass fibres are added to the blended sand-cement matrix to ensure high flexural resistance and ductility of the hardened GRC composite.

Ability of fibre reinforced concrete composites to absorb energy has been recognised as one of the most important benefits for a long time. By adding fibres, brittle concrete matrix is changed to ductile and therefore impact and fatigue performance is significantly improved. Due to high elastic modulus and tension strength, glass fibres also have a high reinforcing potential of concrete composites. Gopalaratham V. S. recommends avoiding fibre reinforced concrete toughness characterisation only by first-crack strength. Instead, he offers to incorporate energy absorption capacity in design. Limits of deflection and crack-width should be serviceability-related and application-specific [7].

Acrylic polymers were used as GRC curing agents for many years. Their primary utility was to eliminate 7-day curing period to achieve 28-day curing strength, which means that GRC products can be placed directly in the stockyard after demoulding instead of curing chambers. Modern superplasticizers help to significantly reduce w/c ratio and global GRC production practice shows, that implementation of acrylic polymers is not necessary anymore [1]. Although, some scientists and manufacturers are advocating benefits on mix workability and composite durability when acrylic polymers are used [8,9].

Abe J. studied self-compacting GRC mixtures with various admixtures (Air-entraining and high-range water-reducing admixture, Separation reduction type water-reducing admixture, Powdered acrylic polymer, Methylcellulose, High performance thickener, Antifoaming agent and micro silica). For all recipes, w/c ratio was 0.30, fibre content 3.0% and OPC-quartz sand ratio 1:1. Best flow was achieved with separation reduction type additive and flexural strength of tested plates varied from 11 to 15 MPa [10].

Peter I.D. investigated the impact of SCC GRC additives on flexural strength with reference to fibre content, fibre length, water/cement ratio, and workability. CEM I 52.5R was used as a binder, polycarboxylic ether-based superplasticizer as a water reducing admixture and quartz sand as a filler. Test showed, that flexural strength increased from 8 to 12 MPa when w/c was reduced from 0.42 to 0.32. Effect of fibre content for flexural strength was more significant than fibre length when fibres used were 13 mm and 25 mm by length. 13 mm fibres resulted in 9 MPa and 25 mm- 10 MPa (3% of total mix weight). For 13 mm fibres, flexural strength increased from 8 MPa to 13 MPa when fibre content was increased from 2% to 4% [11].

Ali M.A. studied first generation alkali resistant glass fibres almost half a decade ago- in 1975. Fibres chosen were 10 mm to 40 mm by length and 2% to 8% mass fraction from total dry materials weight. GRC samples were produced by spray-suction method and 6% fibre content was indicated as most optimal for this method, which resulted in 4-5 times higher bending strength compared to unreinforced matrix [12].

Driver M. tested workability, hydration and durability of GRC mix with finely ground pumice pozzolan. Results showed that cement replacement up to 20% with pumice pozzolan reduces workability time down to only 5 minutes and does not have a significant effect on mechanical characteristics of concrete [13].

Along with the application of glass fibres, the modern researchers are interested in studying of basalt fibres. Basalt fibre is a natural material based on volcanic rocks with a melting temperature in the range of 1500-1700°C. The main minerals, which form the basalt, are plagiocene and pyroxene. The chemical analysis of basalt composition demonstrates that SiO₂ and Al₂O₃ are the main components. The distinctive physical, mechanical, thermal, chemical properties and environmentally
friendly manufacturing process enable the competitiveness of basalt fibre in relation to other types of fibres [14-16].

Current study is focused on investigation of HPC reinforced by glass and basalt fibres with aggregates of different types such as quartz sand and crushed granite.

2. Materials and test methods

In this research paper, different fresh and hardened concrete properties of five GRC formulations are presented. All concrete compositions are given in Table 1. Ordinary Portland cement CEM I 52.5R was used as a binder, crushed granite and quartz sand as fillers and polycarboxylic ether-based plasticiser as the water reducing agent. Properties of aggregates are given in Table 1.

| Properties          | Quartz sand | Granite |
|---------------------|-------------|---------|
| $d_{\max}$, mm      | 1.25        | 2       |
| Bulk density, kg/m$^3$ | 1640        | 1530    |
| Specific gravity, kg/m$^3$ | 2650        | 2800    |
| SiO$_2$,%            | >98.5       | 70-75   |
| Al$_2$O$_3$,%        | <0.6        | 14.4    |
| Water absorption, %  | <0.5        | <0.6    |

Granulometric compositions of quartz and granite fillers are given in Figure 1.

| Properties          | Basalt fibres | Glass fibres |
|---------------------|---------------|--------------|
| Tensile strength, MPa | 3200          | 1400         |
| Modulus of elasticity, GPa | 90            | 74           |
| Thermal resistance,°C | -260…+700     | -50…+380     |
| Melting temperature,°C | 1200          | 1100         |
| Fibre length, mm     | 12.7          | 13           |
| Filament diameter, μm | 17            | 18           |
| Filaments per bundle, pcs | 1500         | 200          |

Figure 1. Granulometric curves of quartz sand and crushed granite

Alkali resistant glass and basalt fibres were chosen for cementitious matrix reinforcement. Properties of fibres are given in Table 2.
For all mixes, quantities of cement, water and plasticiser were kept the same, only types and quantities of aggregates and fibres were changed. For compositions G1 and G3, crushed granite was added to change a significant portion of quartz sand. High shear mixer with up to 800 rpm was used for batching. Water, cement, plasticiser and aggregates were blended for 120 s with maximum revolutions (800 rpm). After that, fibres were added and dispersed into the cementitious matrix with 300-400 rpm- 60 s for glass fibres and 30 s for basalt fibres due to severe de-filamentation of basalt. Concrete compositions and mix granulometries are given in Table 3 and Figure 2.

### Table 3. Concrete compositions in kg/m³

| Mix no. | CEM I 52,5R | PCE<sup>a</sup> | W/C | Quartz sand | Crushed granite | Glass fibres | Basalt fibres |
|---------|-------------|----------------|-----|-------------|-----------------|--------------|---------------|
| G1      | 807         | 1.1%           | 0.36| 403         | 403             | 48           | 0             |
| G2      | 807         | 1.1%           | 0.36| 807         | 0               | 48           | 0             |
| G3      | 807         | 1.1%           | 0.36| 121         | 686             | 48           | 0             |
| B1      | 807         | 1.1%           | 0.36| 403         | 403             | 0            | 24            |
| B2      | 807         | 1.1%           | 0.36| 807         | 0               | 0            | 24            |

<sup>a</sup> Polycarboxylic ether-based superplasticiser

![Figure 2. Granulometric curves of G1, G2 and G3 aggregate mix](image)

Workability of fresh concrete was tested according EN1170-1, which is based on a slump test with cylinder Ø65, h=55mm. Flexural and compressive strength was tested according EN196-1. Fracture characteristics was determined according to EN1170-4, by casting concrete boards 525x525x15 mm and cutting them into 8 specimen plates 275x50x15 mm, which were oriented in perpendicular direction. Four plates were tested after 7 days and other four after 28 days, their bending curves have been plotted.

### 3. Results and discussion

#### 3.1. Workability

During concrete preparation, several problems associated with workability were noticed. Different fibre and aggregate type had a major impact on concrete slump. Water bleeding was also significant and associated with crushed granite aggregate.
Figures 3 and 4 show slump and workability for all tested compositions. The highest slump was achieved with quartz sand and glass fibres (G2- 23 cm). Other two compositions with glass fibres (G1 and G3) had much smaller slump- 13 cm and 12 cm respectively. Some water bleeding was also noticed for G1 and G3 due to coarse granite aggregate which tends to bleed water from concrete mix. Glass fibres seemed to stay in bundles even after 1 min of high shear mixing.

![Figure 3. Slump for compositions with glass fibres (G1, G3, G2)](image)

Initial tests with 48 kg/m³ and 36 kg/m³ of basalt fibres resulted in near zero slump and it was decided to do additional tests with 24 kg/m³ (B1, B2). Less fibres improved workability, yet severe fibre bundle de-filamentation was noticed after 30 s of high shear mixing. Slump of B1 and B2 compositions were 16 cm and 12 cm respectively. B2 with 50% granite filler also showed significant water bleeding.

![Figure 4. Slump for compositions with basalt fibres (B1, B2)](image)

3.2. Mix and hardened concrete density

Fresh concrete densities were between 2130-2200 kg/m³ for all compositions (figure 5). During hydration process, densities increased up to 2200-2230 kg/m³. Compositions with granite aggregate (G1, G3, B2) had higher densities for both fresh and hardened concrete than ones with quartz sand and after further mechanical tests showed that higher densities resulted in higher flexural strength.
3.3. Flexural and compressive strength

For compressive and flexural strength, concrete prisms with dimensions of 40x40x160 mm were tested according to EN196-1. Compressive strength after 28 days exceeded definition of high strength concrete (>55MPa, American Concrete Institute). Values of 79.5 MPa and 80 MPa were achieved for G1 and G2, 72.8 MPa and 73.9 MPa for B1 and B2 (Figure 5). This brings us to a conclusion that replacing 50% of quartz sand with crushed granite did not have any influence on compressive strength. On the other hand, compositions with basalt fibre reduced compressive strength by 8 MPa.

Flexural strength was even more emphatic on the influence of aggregate and fibres. Results were 15.15 MPa for G1; 13.4 MPa for G2; 8.9 MPa for B1, 10.1 MPa for B2. This concludes that glass fibres showed up to 70% higher flexural strength than basalt and replacing 50% quartz sand with granite aggregate increased flexural strength by 13%.

3.4. Fracture characteristics

Flexural tests showed that glass and basalt fibres significantly increase ductility of concrete matrix. Flexural strength also corresponded to values, reported by other scientists that have been developing self-compacting GRC premix.

Bending curves in Figure 7 show that coarse shape of granite aggregate has a positive influence, increasing 7-day flexural strength by 3 MPa and 28-day by 1 MPa, when 50% of quartz sand is replaced by granite (G1). Ductility of glass fibre reinforced composite is apparent, and no brittle behaviour was found during the bending tests. All specimens reached their rupture point at average deflection to span ratio 1/250, which was characterized as the first crack in the tension zone. Even after deflection increased by 400% from rupture point, specimens were still maintaining up to 90% of maximum resistance.
On the other hand, basal fibres showed little effect on ductility of concrete matrix, resulting in a brittle behaviour (Figure 8) and specimens lost up to 80% of maximum strength when flexural strain increased by 400% from rupture point.

Table 4 shows residual strength for tested compositions at 3 mm stroke, indicating high ductility of glass fibre reinforced composite and brittle behaviour of basal fibre reinforced compositions.

Table 4. Residual flexural strength at 3 mm stroke (plates 15x50x275, 28 days)

| Composition | Flexural strength, MPa | Residual strength at 3mm deflection, MPa |
|-------------|------------------------|----------------------------------------|
|             | after 7 days | after 28 days | after 7 days | after 28 days |
| G1          | 10.8         | 11.5         | 9.8         | 10.0         |
| G2          | 7.7          | 10.0         | 5.9         | 9.0          |
| G3          | 9.0          | -            | 8.8         | 8.6          |
| B1          | -            | 9.5          | -           | 1.8          |
| B2          | 6.2          | 8.0          | 2.2         | 2.0          |

4. Conclusions
Workability of glass and basalt fibre reinforced concrete is better when quartz sand aggregate is used. Replacing 50% of quartz sand with crushed granite significantly reduces workability and some water bleeding start to occur.

Basalt fibres are disintegrating from bundles to single filaments in the concrete matrix during high shear mixing process, therefore workability of the concrete mixture becomes very poor. Despite
promising mechanical characteristics of basalt, glass fibres are a much more effective choice for self-compacting premix.

Glass fibres increased 28-day flexural strength up to 11 MPa of concrete with granite aggregate, changing concrete from a brittle to a highly ductile composite material. Specimens with basalt fibres had up to 9.5 MPa flexural strength and very low ductility.

Replacement of 50% of quartz sand with crushed granite had a positive influence on mechanical characteristics, increasing 7-day flexural strength by 30% and 28-day by 10%.

28-day compressive strength was up to 80 MPa for concrete with glass fibres and 74 MPa for basalt passing the criteria for high performance concrete.

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