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Effect of aggregate particle shape and granulometry on the workability and mechanical properties of glass reinforced concrete

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Abstract. Modern alkali resistant glass fibers (ARG) modified with 17% ZrO_2 are getting more popular as reinforcement of cementitious matrixes. Typical matrix compositions with quartz, Portland cement, 13 mm length ARG glass fibres and PCE superplasticizer can offer good workability, product quality and highly increased mechanical characteristics. In production of self compacting fibre reinforced premix highly siliceous fine sands with nearly round shape particles are usually preferred. This article investigates influence of particle shape for workability of glass fibre reinforced concrete when alternative fillers- crushed granite and regular sand are used. 12 compositions were made whith different quantities of fillers, changing quartz from 0% to 50% with alternative aggregates. Slump tests according to EN 1170-1 were made and showed major impact of particle shape characteristics on mix workability. When quantity of altrernative aggrates was increased, slump of fresh mix decreased and fibre- matrix segregation occurred. New workability factor W is offered and values calculated, to have numeric representation of workability. Alternative aggregates had no clear influence for flexural strenght, when beams 40×40×160 were tested. Compressive strength dropped by 25% when regular sand was used. Typical quartz matrix resulted in lower water absorbtion.

Keywords: glass reinforced concrete, glass fibers, workability, particle shape.

Introduction

Self-compacting glass fibre reinforced concrete (GRC) is becoming popular composite material in the field of various prefabricated decorative concrete elements, from façade claddings to flowerpots. Cementitious quartz matrix is easy to to work with and offers good overall characteristics, from workability to flexural strength.

One of the most common GRC production techniques is premix method, when mortar and precut fibers are mixed together before casting. The quantity of fibers added to the mortar is usually up to 3.5%, in terms of weight, and the length of the fibers is around 12 mm. Longer fibers lead to an excessive reduction of the mix workability therefore are rarely used (Bentur & Mindess, 1990). Another technique is spray method, when glass fibre strand is chopped and sprayed together with mortar on the mould surface. In this article, only first (premix) method is investigated.

As climate change is getting more and more debated topic, we should not forget other two main challenges, directly associated with building sector- durability of construction materials and remaining resourses for new products for construction market. According to The American Society of Civil Engineers (ASCE) calculations, the average maintenance- free life for a structure built today is approximately only 18.5 years (Abanilla et al., 2006). In Lithuania there is only one quarry of pure quartz sand, perfect for GRC. If consumption will not change, it will last only for 30 years more. Current estimation of available sand- gravel resourses in Lithuania is about 506 milion tons, which means we have enough for 67 more years. For reasons above it is very important to search for alternative GRC matrix fillers instead of quartz sand.

Since 1956 there has been a huge amount of research and development work carried out in the field of glass reinforced cementitious composites and for that reason, GRC can be considered as a trustful building material for various applications when ZrO_2 modified glass is used (Vahidi & Malekabadi, 2011; Rickard, 2015). In 1970's Majumdar A. J. produced alkali resistant glass filaments diameter around 10 μm according to single tip furnace method and tested it for reaction with Portland cement in various temperatures from 20 °C to 65 °C. Durability tests showed that new Zirconia modified glass filament still loses a portion of its pristine strength in alkali environment. Reaction speed is increasing together with temperature, but at ambient temperatures of 20 °C no significant loss of strength was recorded, and long-term tensile strength of Zirconia modified glass was recorded of around 1200 MPa (Majumdar, West, & Larner, 1977). Latest scientific investigations offer vide variety of methods to improve durability of glass fibre reinforced cementitious composites. Some propose to add polymers (Qian, Shen, Mu, & Li, 2003), others- to incorporate microfillers (Brandt & Glinicki, 2003; Peled, Jones, & Shah, 2005; Bartos & Zhu, 1996), or modify fibre surface with organo-silane and carbon nanotube reinforced Nano clay coatings (Rothe, Gao, Plonka, & Mader, 2015; Mader & Plonka, 2004; Gao, Mader, & Plonka, 2007).

Although there has been (and still is) a tremendous thrust in research programmes to seek for more fibre alternatives, the fibre cement composite producers worldwide have used only a few of the fibre types researched today, one of them being alkali resistant glass fibres (ARG). The reason for this is that choice of a particular fibre type is based on price, availability, compatibility with cement, durability and the reinforcing potential in the cement composite (Akers, 2006). Possible alternative for currently used AR glass fibre in near future might become carbon and basalt when new fibre production techniques will offer significantly lower prices, better durability and cementitious mix workability (High, Seliem, El-Safty, & Rizkalla, 2015; Xu, Liu, & Li, 2015).

Some scientific studies show that flexural capacity of self compacting glass reinforced premix is between 9–15 MPa, depending on fibre content and additives used. Peter I. D. investigated 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 binder, polycarboxilic ether-based superplasticizer as water reducing admixture and fine silica sand as filler. Tests 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% (Peter & Crocker, 2015). 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 (Abe, Takeuchi, Ogata, & Imai, 2011).

Annother important factor, influencing mechanical characteristics of concrete is granulometric composition. There are no scientific research addressing this issue for glass fibre reinforced concrete. In general theory, the packing density of a granular mix is defined as the solid volume Φ in a unit total volume. Alternatively, the compaction may be described by the porosity ($\pi = 1 - \Phi$). In the past, the design strategy has generally been to proportion the different grains to obtain a grading curve close to an 'ideal' grading curve, which is supposed to produce the maximum packing density. The packing density of a polydisperse grain mixture depends on three main parameters: the size of the grains considered (described by the grading curves), the shape of the grains and the method of processing the packing (de Lerrard, 1999).

Materials and test methods

12 GRC compositions were tested for workability and flexural toughness. 3 types of aggregates with different particle size and shape were used to identify their influence for mix workability. Other components were kept constant. Manufactured in Lithuania Portland cement CEM I 52,5R was used as a binder. Fine granite, quartz and regular sand were chosen as aggregates. Polycarboxilic ether- based superplasticizer was chosen as a water reducing agent and alkali resistant (AR) glass fibers for matrix reinforcement.

Chemical composition of CEM I 52,5R is given in Table 1. Its specific (blaine) surface was 5100 cm^2/g, particle density 3.13 g/cm^3 and mean diameter of particles- 9.31 μm. Particle size distribution is given in Figure 1.

Table 1. Chemical composition of cement

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Na_2O_{eq}	Cr
CEM I 52,5R	63.99	19.84	5.24	2.99	1.55	3.05	0.78	0.25	0.76	0.062

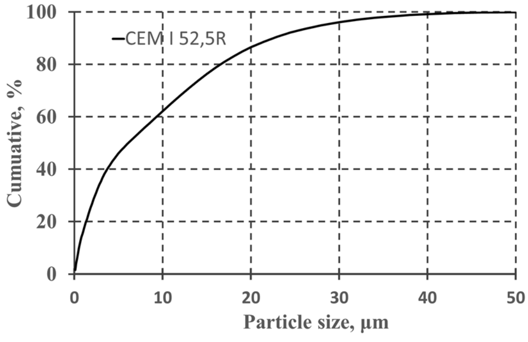


Figure 1. Particle size distribution of Portland cement CEM I 52,5R

Properties of aggregates are given in Table 2, granulometrical compositions of all fillers are given in Figure 2. Quartz has narrow particle distribution with 90% of particles between 0.125–0.5 mm. Granite and regular sand has almost identical granulometries with even distribution between 0.125–2 mm.

Table 2. Main Properties of aggregates

Properties	Quartz	Granite	Regular Sand
d_{max}, mm	0.5	2	2
Bulk density, kg/m^3	1640	1530	1450
Specific gravity, kg/m^3	2650	2800	2600
Water absorption, %	<0.5	<0.6	<0.5

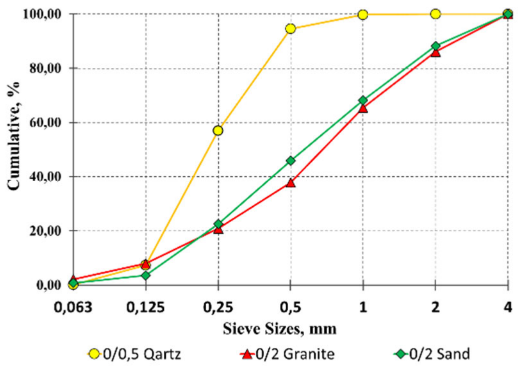


Figure 2. Particle size distribution of used aggregates- quartz, granite and regular sand

Each fibre is a bundle of 200 filaments with diameter of 18 µm. Filaments are layered on each other in series, giving a flat rectangular shape of the fibres, with total width about 1.5 mm. Length of fibres was 13 mm, tensile strength 1400 MPa, modulus of elasticity 74 GPa and melting temperature, common for glass- 1100 °C.

Mix compositions were divided into two groups- G and S and are given in Table 3. Quantities of cement and fillers are given in proportions, superplasticizer is in percentage from mass of cement and glass fibres in percentage from the mass of whole matrix.

High shear mixer with up to 800 RPM was used for batching. Water, cement, plasticizer and aggregates were blended for 120s with maximum revolutions (800 RPM). After that, glass fibres were added and dispersed into the cementitious matrix with 300–400 RPM for 60 seconds.

Table 3. Relative compositions

Materials	G0	G1	G2	G3	G4	G5	S0	S1	S2	S3	S4	S5
CEM I 52,5R	1	1	1	1	1	1	1	1	1	1	1	1
Superplasticizer	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%
W/C	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36
Quartz 0/1.25	1	0.9	0.8	0.7	0.6	0.5	0	0.9	0.8	0.7	0.6	0.5
Granite 0/2	0	0.1	0.2	0.3	0.4	0.5	0	0	0	0	0	0
Sand 0/2	0	0	0	0	0	0	1	0.1	0.2	0.3	0.4	0.5
Glass fibre	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%

Beams 40×40×160 were produced to test flexural and compressive strength after 28 days according to EN 196-1. Workability of fresh concrete was tested according EN 1170-1, which is based on a slump test with cylinder Ø65, $h = 55$ mm.

Results and discussion

Concrete densities

Glass fiber reinforced concrete is a polydisperse grain mixture, consisting of two dominant particle size distribution intervals with close to equal proportion: D1<20 µm (cement) and D2 = [125...2000 µm] (filler). Glass fibre inclusions are occupying <5% of total mix volume. As particles of the filler are relitevely close to each other, any variations of filler granulometry or particle shape could have influence on concrete workability (Figure 3). Fresh mix densities for G and S compositions are ranging from 2196 kg/m^3 to 2248 kg/m^3 and are given in Figure 4. Hardened concrete densities were ranging from 2069 kg/m^3 to 2133 kg/m^3.

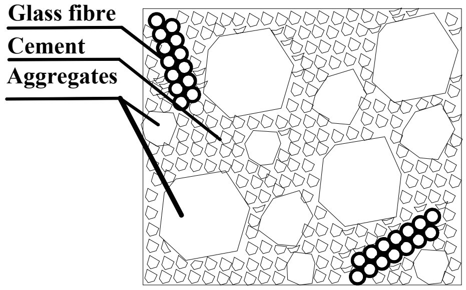


Figure 3. Particle size distribution of typical GRC mix

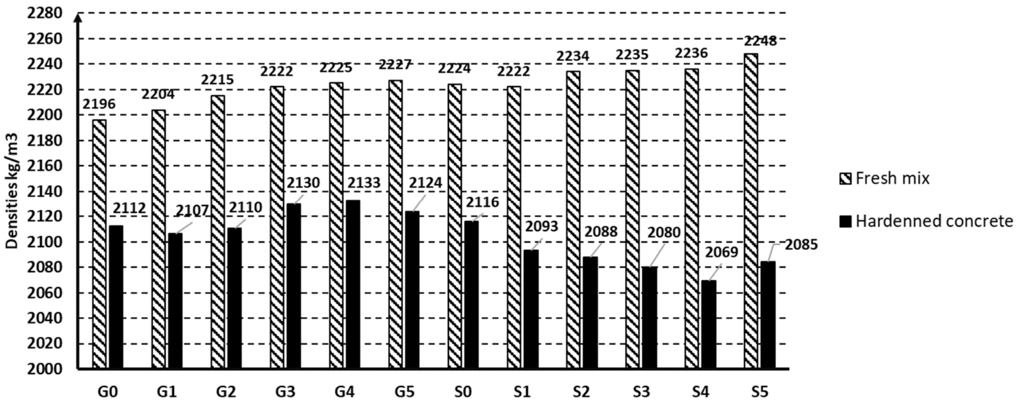


Figure 4. Fresh mix and hardened concrete densities

Workability

It is relatively easy to make self-compacting glass fibre reinforced premix when quartz filler is used (G0 mix). Other fillers, such as crushed granite or regular fine sand results to water bleeding and segregation. In order to investigate this effect, several mix compositions were prepared by changing quartz matrix with 10%, 20%, 30%, 40%, 50% and 100% alternative fillers (granite or regular sand). Fibre- matrix segregation was noticeable in all modified compositions and for this reason, several parameters were introduced to typical GRC workability test according to slump method EN-1170-1 (Figure 5).

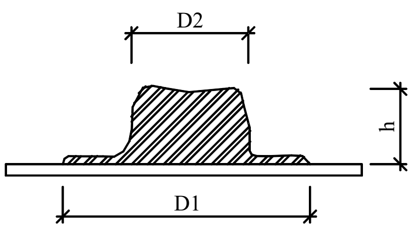


Figure 5. Additional GRC workability parameters to EN1170-1

According to scheme given in Figure 5, we can state that workability index W is directly proportional to $D1$ and $D2$, but indirectly to h. This can be written as:

$$W = (D1 \cdot D2) / h, \text{ cm.} \quad (1)$$

If we assume, that for typical self-compacting GRC $D1 = D2 = 22$ cm, and $h = 1.3$ cm, then we get $W = 372$ cm. Workability indexes for all compositions are given in Table 4 and workability parameters in Figure 6. As we can see, added alternative fillers to the quartz matrix decreases mix workability. Particle size distributions of crushed granite and regular sand are very similar, even though there is a clear difference in workability (Figure 7).

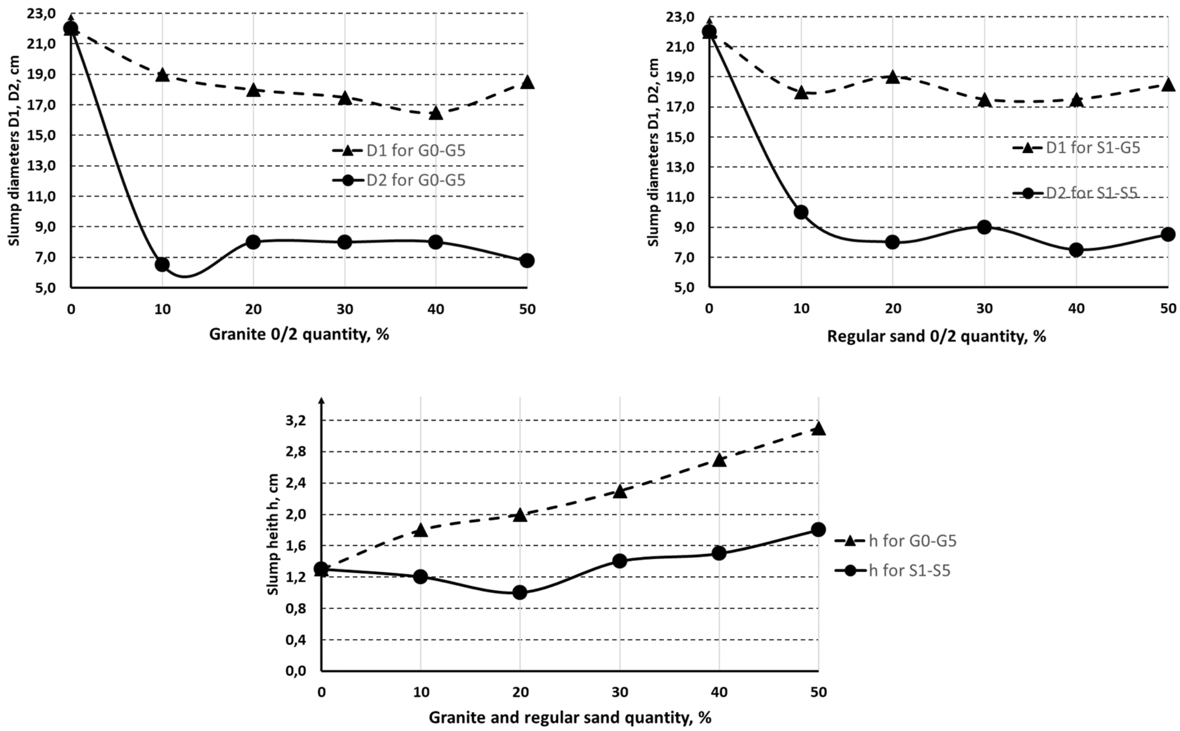
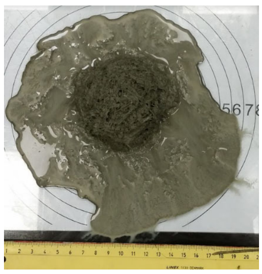


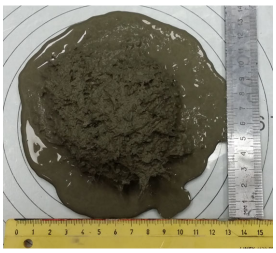
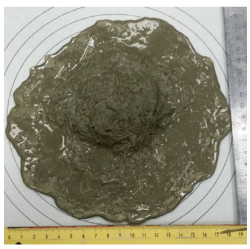
Figure 6. Workability parameters *D*1, *D*2 and h for compositions with granite and regular sand

Table 4. Workability indexes

	G0	G1	G2	G3	G4	G5	S0	S1	S2	S3	S4	S5
W	372	69	72	61	49	40	45	150	152	113	88	87

a) b)

c) d)

Figure 7. Workability test: a) composition G0 (quartz matrix); b) G5 (50% qyartz replaced by granite); c) S0 (typical sand matrix); d) S5 (50% of quartz replaced by sand)

This difference can be explained by particle shape. Quartz sand particles have close to round shape, resulting into good flow of the mix, because there is little interaction between aggregate itself and aggregate to fibres. Granite has particles with sharp edges, which creates crowding effect between glass fibres and aggregate and results in fibre- matrix segregation. Regular sand has multangular particles with less sharp edges than granite, which result in better workability. These ideas are represented graphically in Figure 8.

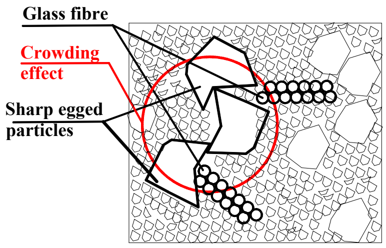


Figure 8. Graphical representation of matrix segregation in compositions with sharp shape particles (crowding effect)

Compressive strength

Compressive tests showed that highest packing density and compressive strength of 82.97 MPa is achieved with quartz matrix (G0). Changing 50% of quartz with granite reduced compressive strength by 17% down to 68.59 MPa. Adding even small amounts (10%) of regular sand to quartz matrix reduces compressive strength significantly, to 63–65 MPa (Figure 9).

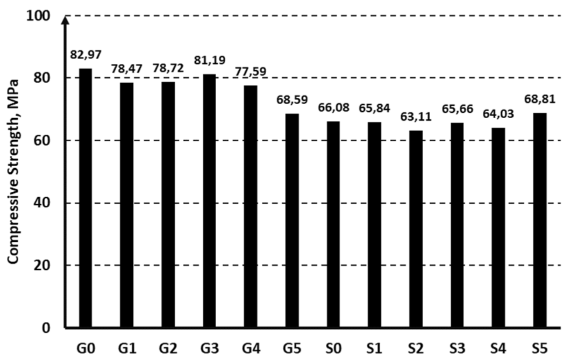


Figure 9. Compressive strength after 28 days

Flexural strength

Prisms 40×40×160 were tested for flexural strength and results varied from 11.34 MPa to 13.4 MPa (Figure 10). Pure quartz gives good flexural capacity (>13 MPa) and modification of matrix with granite or regular sand did not result in increased flexural strength of GRC composite.

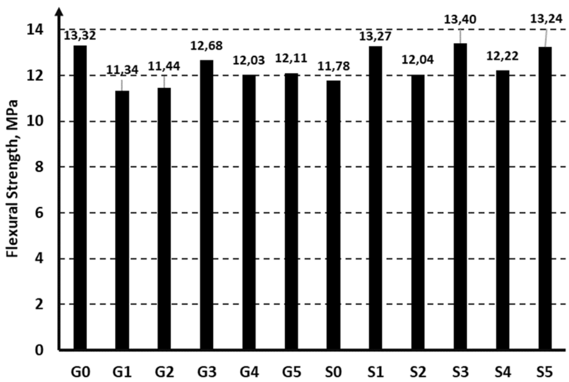


Figure 10. Flexural strength after 28 days

Water Absorption

Due to high content of Portland cement, GRC has higher water absorption, compared to regular concrete. Average values of water absorption after 60 min immersion was 9% and 11.4% after 48 h immersion for prisms 40×40×160. (Figure 11). Lowest water absorption was reached with quartz matrix- 10.8% after 48 h and 8% after 60 min.

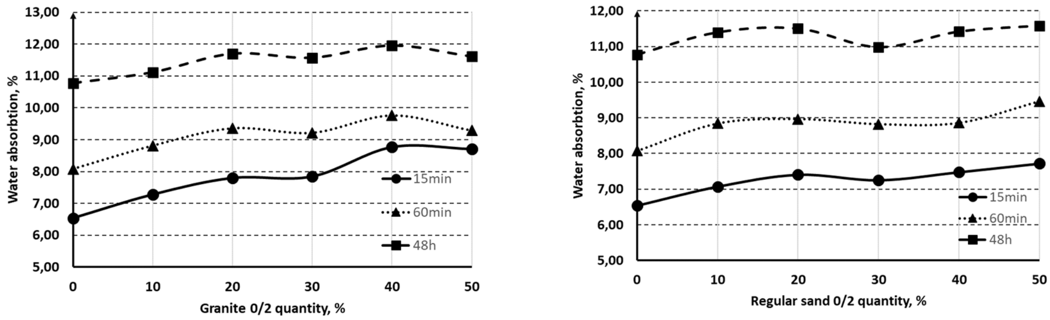


Figure 11. Water absorption of prisms 40×40×160 after 15 min, 60 min and 48 h

Conclusions

Workability and mechanical characteristics of glass fibre reinforced concrete premix with different aggregates was investigated. Alternative fillers- chrushed granite and regular sand were incorporated into typical quartz matrix. When alternative fillers are added, fiber- matrix segregation occurs which can be explained by crowding effect between glass fibres and multangular particles with sharp edges. New concept of workability factor *W* was introduced in this article to supplement standard test method EN1170-1. Changing up to 50% of typical GRC quartz matrix with 0/2 crushed granite increases hardened concrete density by up to 50 kg/m^3 and decreases by 21 kg/m^3, when regular sand is used. Compressive strength with typical quartz matrix is about 83 MPa and it decreases by 17% down to 63 MPa, when granite or regular sand is incorporated. Pure quartz gives good flexural capacity (13 MPa) and modification of matrix with granite or regular sand did not result in increased flexural strength of GRC composite. Lowest water absorption was reached with quartz matrix- 10.8% after 48 h and 8% after 60 min. Water absorption is increasing when alternative fillers (granite and regular sand) are used instead of fine quartz.

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