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**Research paper**

# Comparative influence of active mineral admixtures on the strength properties of fiber-reinforced reactive powder concrete

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**Abstract:** The use of active mineral admixtures in concrete and reinforced concrete technology is one of the most important ways to save resources. Silica fume is one of this type's most popular and effective admixtures. However, the use of silica fume is not always economically reasonable due to its high cost. The paper presents the results of comparative studies on the effect of various active mineral admixtures on the properties of reactive powder concrete (RPC) and fiber-reinforced powder concrete (FRPC). Five different admixtures were investigated: ground quartz sand, blast furnace slag, fly ash, metakaolin and silica fume. The highest strength values were achieved for RPC and FRPC containing microsilica and fly ash together with metakaolin. The RPC compositions containing fly ash and metakaolin achieved at 28 days an average compressive strength of approximately 125 MPa and a flexural strength of over 16 MPa. This is only an average of 10–20% less compared to concrete containing silica fume, however the cost of silica fume is about 2–3 times higher compared to fly ash and metakaolin. Thus, it becomes possible to replace high-cost silica fume with the proposed composite mineral admixture consisting of fly ash and metakaolin. Adding steel microfibers to the tested RPC compositions can increase compressive strength by 10–20%, depending on the composition. With a steel fiber consumption of 240 kg/m$^3$, the flexural strength increases by 1.5 to 2.3 times, reaching 35 MPa.

**Keywords:** active mineral admixtures, reactive powder concrete, silica fume, fly ash, metakaolin

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# 1. Introduction

Reactive powder concrete (RPC) was developed in France in the 1990s as a type of fine-grained concrete that offers increased uniformity, strength, and deformability [1,2]. Typically, RPC has a compressive strength ranging from 150 to 200 MPa, although it can reach 500 to 800 MPa under particular conditions [3,4]. Significant progress in the and use of modern chemical and mineral admixtures, in particular superplasticizers and silica fume [2,5,6].

To achieve ultra-high strength with very low water content, RPC requires high cement dosages of 700–1000 kg/m$^3$. Such high consumption is important for enhancing the hydration process, which allows the formation of a lot of C–S–H gel between a large surface area of the powders, which leads to the compaction of its particles [5]. However, cement hydration in RPC is incomplete, causing a lot of free cement grains to form. These grains are crucial in the packing of granules in RPC. Adding large amounts of cement to the concrete mix has many disadvantages, both in terms of the environment and the hardened concrete behavior. These include high costs and increased heat of hydration, which leads to shrinkage problems and reduced dimensional stability over time. To overcome these problems in RPC, mineral admixtures such as fly ash, blast furnace slag and silica fume can be a practical alternative to replace cement [7–12]. These admixtures improve concrete performance by filling spaces, activating pozzolanic reactions and accelerating cement hydration, which allows the formation of calcium silicate hydrate.

The enhancements obtained from the inclusion of pozzolanic materials in RPC are high tensile and high flexural strengths, early compressive strength, low permeability and high resistance to chemical attack. It also increases abrasion resistance, durability, modulus of elasticity, enhances pore structure and improves adhesion characteristics with steel fibers [6,9,13–15].

Among the most effective pozzolanic materials used in RPC is silica fume [6,13,14,16]. Increasing the steel fibers content above 25% does not significantly change the RPC compressive strength [6,17,18].

The use of ground granulated blast furnace slag is also effective and can be used in RPC as an alternative silica source [9,19–21]. Adding up to 20% fly ash as a partial replacement of cement in concrete modifies the cement stone microstructure and enhances the physical and mechanical properties [9,22,23], especially after exposure to elevated temperatures and pressures [18,20]. As known, fly ash requires less water for reaction compared to silica fume [7].

Highly reactive metakaolin also demonstrates high pozzolanic reactivity. Adding metakaolin to concrete reduces porosity, accelerates the hydration process, enhances resistance to chemical exposure, and improves durability and pore structure [25,26]. It has been found that metakaolin reduces the shrinkage of concrete during curing. This is due to the high amount of reactive $Al_2O_2$ in its composition [27].

With the addition of quartz powder compressive strength increased by up to 20% [28]. In the RPC production quartz sand represents the highest percentage ingredient, accounting for approximately 40% of the RPC weight. Furthermore, the quantity of quartz powder used in RPC production is relatively high, reaching 20% and 35% of the cement weight [28,29].

Compared to conventional concrete, RPC has a higher water demand to avoid a decrease in workability. Therefore, superplasticizers are added to improve the RPC workability despite its low water content. High-performance superplasticizers represented by polycarboxylates, polyacrylates, or naphthalene sulfonates contribute to forming a homogeneous RPC matrix [30]. The optimal superplasticizer dosage is 1–3.5% by the binder weight, depending on the W/B ratio [5, 30].

RPC is the optimal matrix for production of fiber-reinforced concrete. It does not contain coarse aggregate, which can hinder uniform fiber distribution and cause accumulation between aggregate grains. Adding steel fibers to RPC enhances flexural strength, toughness, ductility, and tensile strength [31, 32]. Both high strain and high stress are achieved by increasing the steel fiber content at the same strain rates, resulting in an obvious increase in stiffness [33]. Fibers act as a preventive measure for cracks. It regulates the development of cracks and impedes their expansion within the concrete matrix, thereby inhibiting the cracks propagation [30]. This transformation of a brittle mixture into a more ductile composition with enhanced crack resistance can be achieved, as evidenced by the 160% increase in ductility observed in beams with 2.0% fiber content [17]. It is also known that inclusion of high amounts of steel fibers in concrete is followed by a loss of workability and homogeneity of the mixture [32, 35]. Therefore, there is an optimal fiber content for any RPC matrix.

Composite admixtures to RPC consisting of two or more components are promising and can enhance their integrated effect in cement systems. The efficiency of combined fly ash-containing admixtures has been demonstrated in many studies [36, 37]. Selecting the correct combination of components for combined admixtures is a complex problem that requires special studies in each case, considering technological, technical and economic factors.

In the context of modern circumstances, silica fume represents a scarce component, and the process of transportation and dosing presents certain difficulties. The research results about the influence of alternative mineral admixtures on the properties of special types of concrete are known. The incorporation of extremely fine fly ash or metakaolin for replacement of silica fume [38], the use of a mineral admixture containing fly ash in RPC [39] and using fly ash and slag as alternative silica- containing mineral admixtures for RPC [9, 40, 41] are examples of various approaches currently being employed. However, there is a limited data on the application of fly ash in combination with metakaolin in RPC and the impact of terms of curing on mechanical properties of such concrete.

The present study is aimed at comparing the strength properties of RPC and FRPC with different mineral admixtures and evaluating the possibility of partial or complete replacement of silica fume in RPC by more available admixtures. The main novelty of the present study is development of a complex admixture, the components of which have a synergistic effect on the RPC properties. With this aim are used fly ash that has low pozzolanic activity and water demand and metakaolin that has high pozzolanic activity and water demand. It was assumed that combination of these admixtures would have a synergistic effect on the RPC properties. It is demonstrated that replacing expensive silica fume with this complex admixture is possible and significantly decreases the cost of concrete.

## 2. Materials and methods

The tests were carried out using Portland cement CEM I 42.5 with 6.5% of C3A, 61.5% of C3S and specific surface of 380 $m^2$/kg. Locally available natural quartz sand with a fraction size of 0.16 to 0.63 mm was used as aggregate for RPC.

As mineral admixtures were used ground quartz sand (GQS) with a specific surface area $A_s = 378$ $m^2$/kg, ground granulated blast furnace slag (GS) ($A_s = 273$ $m^2$/kg), fly ash from Burshtyn (Ukraine) TPP (FA) ($A_s = 253$ $m^2$/kg), metakaolin, which is a product of firing kaolin clays ($A_s = 1012$ $m^2$/kg). For comparison, RPC was also obtained using silica fume SikaFume-HR/TU (SF Sika) ($A_s = 2315$ $m^2$/kg). The chemical compositions of the admixtures used are given in Table 1.

Steel microfibers with a length of 13 mm and a diameter of 0.25 mm were used for the dispersed FRPC reinforcement (Fig. 1). The properties of steel microfibers are shown in Table 2.

Table 1. Chemical compositions of admixtures

| **Admixtures** | **Chemical composition, %** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **SiO2** | **$Al_2O_2$** | **$Fe_2O_2$** | **CaO** | **MgO** | **$Na_2O + K_2O$** | **L.O.I** |
| Blast furnace slag | 39.52 | 6.49 | 0.12 | 47.13 | 3.10 | – | – |
| Fly ash | 56.91 | 22.68 | 9.60 | 3.61 | 1.65 | 1.66 | 3.85 |
| Metakaolin | 54.50 | 43.11 | 0.34 | 0.30 | 0.25 | 1.05 | 0.51 |
| Silica fume | 93.81 | 0.82 | 0.51 | 0.72 | 0.85 | 1.81 | 0.35 |

Fig. 1. Steel microfibers used in the research

Table 2. Properties of steel microfibers

| **Properties** | **Length, mm** | **Diameter, mm** | **Density, kg/$m^3$** | **Tensile strength, MPa** | **Aspect ratio** | **Modulus of elasticity, GPa** |
|---|---|---|---|---|---|---|
| Specification | 13 | 0.2 | 7800 | 2600 | 65 | 250 |

The RPC compositions were selected based on component ratios determined through test batches, resulting in concrete mixes with maximum workability and high strength. After analyzing various compositions with similar cement consumption, a base optimal composition was selected. The mineral admixture's content was selected to maximize cement savings while maintaining the same strength value at a given flow spread of mixture, based on the results of preliminary experiments [42].

The fresh concrete W/C ratio was determined by measuring slump flow according to EN 12350-8. The slump flow for all mixtures was 550-600 mm. With such a flow, the concrete cone slump is 26-27 cm (according to EN 12350-2), as previous experiments have shown. Such flow values were achieved by adjusting consumption of superplasticizer. Mapei Dynamon SP3, a polyacrylate superplasticizer, was used throughout the experiment. The FRPC production has included adding steel microfibers to the superplasticizer and mixing for about 40-60 s by a laboratory mixer. The fibers were added in a small amount to avoid fiber balling and produce concrete with uniform materials consistency. After that, cement was added to the loosed fiber and mixing continued until a homogenous suspension was obtained. At the following stage, the quartz sand and mineral admixture were added while continuously mixing. Following such technology avoids fiber clumping and enables obtaining a concrete mix with necessary homogeneity. Cube specimens with edges of 10 cm and prisms of 4×4×16 cm were prepared for each batch. The compressive and flexural strength were determined after 1, 7, and 28 days of curing at normal conditions (relative humidity of over 90% and temperature of 20 ±2°C). The flexural strength was determined by a three- point test procedure.

Compressive strength tests of reactive powder concrete specimens are performed in accordance with EN 12390-3. For flexural tests of 4×4×16 cm beams, EN 196-1 is used. For each concrete composition, three specimens were made, for which the average value was calculated. The statistical error for all experimental values did not exceed 6.2%.

The experiments used four RPC compositions (matrices) to produce FRPC with various steel microfiber contents. Concrete compositions are given in Table 3.

Table 3. Concrete compositions

| **Components** | **Units** | **Components' content** | | | | |
|---|---|---|---|---|---|---|
| | | **RPC 1** | **RPC 2** | **RPC 3** | **RPC 4** | **RPC 5** |
| Portland cement | kg/m$^3$ | 750 | 750 | 750 | 750 | 750 |
| Quartz sand | kg/m$^3$ | 1130 | 1130 | 1130 | 1130 | 1380 |
| Ground quartz sand | kg/m$^3$ | 350 | | | | |
| Ground blast furnace slag | kg/m$^3$ | | 350 | | | |
| Fly ash | kg/m$^3$ | | | 350 | 275 | |
| Metakaolin | kg/m$^3$ | | | | 75 | |
| Silica fume | kg/m$^3$ | | | | | 112 |
| Mapei Dynamon SP3 | % of cement weight | 1.5 | 1.35 | 1.65 | 1.42 | 1.62 |
| W/C ratio | — | 0.253 | 0.259 | 0.269 | 0.255 | 0.260 |

The specific cement consumption (specific efficiency of cement use) per unit of concrete strength ($C_f$) was calculated to select the effective RPC and FRPC compositions:

$$C_f = \frac{C}{f_{cm}} \quad \text{or} \quad C_f = \frac{C}{f_{c,tf}} \tag{2.1}$$

where: $C$ – the cement consumption per 1 m$^3$ of concrete, kg; $f_{cm}$ – compressive strength, MPa, $f_{c,tf}$ – flexural strength of concrete, MPa.

The specific fiber consumption (specific efficiency of fiber use) per unit of concrete strength was also determined for fiber-reinforced concrete:

$$F_f = \frac{F}{f_{cm}} \quad \text{or} \quad F_f = \frac{F}{f_{cm}} \tag{2.2}$$

where: $F$ – the fiber consumption per 1 m$^3$ of concrete, kg.

## 3. Results and discussion

Tables 4–6 show the results of experiments comparing the effects of various mineral admixtures with and without using steel fibers. The standard deviation and variation coefficients of the test results given in Tables 4–6 are in the range of 1.5 MPa and 6.7 MPa (3.5% and 11.8%, respectively).

Table 4. Technological indicators and strength properties of reactive powder concrete

| **Indicators** | **RPC 1** | **RPC 2** | **RPC 3** | **RPC 4** | **RPC 5** |
|---|---|---|---|---|---|
| W/C | 0.253 | 0.259 | 0.269 | 0.255 | 0.260 |
| Compressive strength, MPa | | | | | |
| $f^1_{cm}$ | 34.1 | 41.3 | 39.4 | 44.0 | 39.6 |
| $f^7_{cm}$ | 69.4 | 84.1 | 80.3 | 89.6 | 76.2 |
| $f^{28}_{cm}$ | 99.5 | 120.6 | 115.1 | 128.4 | 140.6 |
| Flexural strength, MPa | | | | | |
| $f^1_{c,tf}$ | 8.5 | 8.2 | 7.9 | 8.4 | 11.6 |
| $f^7_{c,tf}$ | 10.2 | 11.1 | 10.5 | 11.1 | 14.3 |
| $f^{28}_{c,tf}$ | 14.2 | 14.9 | 14.92 | 16.2 | 18.7 |
| Relative and specific indicators | | | | | |
| $f^{28}_{cm}/f^{28}_{c,tf}$ | 7.01 | 8.09 | 7.71 | 7.93 | 7.52 |
| $C/f^{28}_{c,tf}$, kg/MPa | 52.8 | 50.3 | 50.3 | 46.3 | 40.1 |
| $C/f^{28}_{cm}$, kg/MPa | 7.5 | 6.2 | 6.5 | 5.8 | 5.3 |

Note: RPC compositions marking is according to Table 3.

Table 5. Technological indicators and strength properties of FRPC with a fiber consumption of 1.54% vol.

| **Indicators** | **FRPC 1** | **FRPC 2** | **FRPC 3** | **FRPC 4** | **FRPC 5** |
|---|---|---|---|---|---|
| W/C | 0.257 | 0.260 | 0.265 | 0.261 | 0.265 |
| Compressive strength, MPa | | | | | |
| $f_{cm}^{1}$ | 38.6 | 44.2 | 43.0 | 50.4 | 46.1 |
| $f_{cm}^{7}$ | 78.5 | 89.9 | 87.6 | 102.6 | 99.2 |
| $f_{cm}^{28}$ | 112.5 | 128.9 | 125.6 | 147.1 | 155.4 |
| Flexural strength, MPa | | | | | |
| $f_{c,tf}^{1}$ | 7 | 7.6 | 7.2 | 8.1 | 13.3 |
| $f_{c,tf}^{7}$ | 16.3 | 18.6 | 15.6 | 18.1 | 24.5 |
| $f_{c,tf}^{28}$ | 23.8 | 24.1 | 22.1 | 28.8 | 33.6 |
| Relative and specific indicators | | | | | |
| $f_{cm}^{28}/f_{c,tf}^{28}$ | 4.74 | 5.35 | 5.69 | 5.12 | 4.63 |
| $C/f_{c,tf}^{28}$, kg/MPa | 31.6 | 31.1 | 34.0 | 26.1 | 22.3 |
| $C/f_{cm}^{28}$, kg/MPa | 6.7 | 5.8 | 6.0 | 5.1 | 4.8 |
| $F/f_{c,tf}^{28}$, kg/MPa | 5.05 | 4.98 | 5.43 | 4.17 | 3.57 |
| $F/f_{cm}^{28}$, kg/MPa | 1.07 | 0.93 | 0.96 | 0.82 | 0.77 |

Note: FRPC compositions marking is according to Table 3.

Table 6. Technological indicators and strength properties of FRPC with a fiber consumption of 3.08% vol.

| **Indicators** | **FRPC 1** | **FRPC 2** | **FRPC 3** | **FRPC 4** | **FRPC 5** |
|---|---|---|---|---|---|
| W/C | 0.263 | 0.271 | 0.273 | 0.269 | 0.272 |
| Compressive strength, MPa | | | | | |
| $f_{cm}^{1}$ | 42.4 | 47.4 | 47.5 | 52.5 | 49.2 |
| $f_{cm}^{7}$ | 86.2 | 96.5 | 96.7 | 106.9 | 115.4 |
| $f_{cm}^{28}$ | 123.6 | 138.3 | 138.7 | 153.2 | 162.3 |
| Flexural strength, MPa | | | | | |
| $f_{c,tf}^{1}$ | 10.7 | 11.6 | 12.5 | 13.1 | 15.6 |
| $f_{c,tf}^{7}$ | 26.6 | 28.9 | 26.2 | 27.2 | 33.4 |
| $f_{c,tf}^{28}$ | 31.5 | 33.7 | 28.5 | 36.6 | 42.1 |
| Relative and specific indicators | | | | | |
| $f_{cm}^{28}/f_{c,tf}^{28}$ | 3.92 | 4.10 | 4.87 | 4.19 | 3.86 |
| $C/f_{c,tf}^{28}$, kg/MPa | 23.8 | 22.3 | 26.3 | 20.5 | 17.8 |
| $C/f_{cm}^{28}$, kg/MPa | 6.1 | 5.4 | 5.4 | 4.9 | 4.6 |
| $F/f_{c,tf}^{28}$, kg/MPa | 7.62 | 7.12 | 8.42 | 6.56 | 5.70 |
| $F/f_{cm}^{28}$, kg/MPa | 1.94 | 1.74 | 1.73 | 1.57 | 1.48 |

Note: FRPC compositions marking is according to Table 3.

The data analysis shows that the best strength characteristics are achieved for RPC of the fifth composition (RPC5). By using silica fume as an admixture, a compressive strength of 140 MPa and a flexural strength of over 19 MPa were obtained after 28 days (see Fig. 2). It is generally consistent with the known data presented in [13, 17]. The addition of a finely ground admixture in a form of a composition of fly ash and metakaolin (275 + 75 kg/m$^3$) was found to be more effective than using ground quartz sand, slag, or fly ash. Concrete made with this composition achieved an average compressive strength of almost 130 MPa and a flexural strength of over 16 MPa at 28 days (Figs. 2 and 3). Compared to the compositions containing only ash (RPC4 and RPC3), the concrete mixture composition with ash and metakaolin required less water and superplasticizer, resulting in a lower water-cement ratio. The RPC4 mixtures exhibited better workability and fewer visible pores in the test specimens.

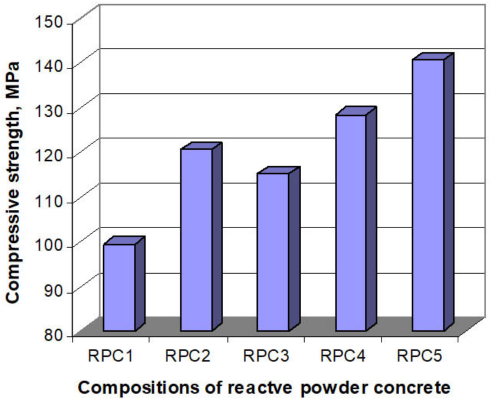

Fig. 2. Effect of RPC composition on compressive strength at 28 days

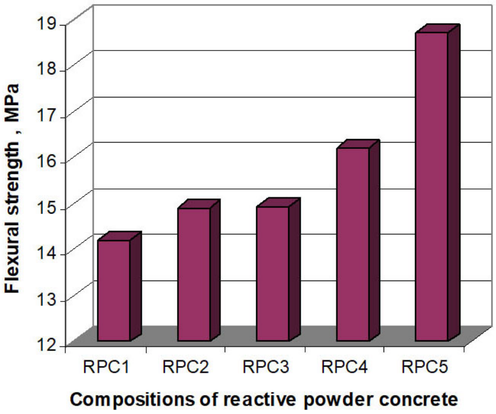

Fig. 3. Effect of RPC composition on flexural strength at 28 days

The water-cement ratio ranged from 0.25 to 0.27, and the water-solid ratio was 0.084 to 0.09. The ductile (plastic) nature of specimen destruction is determined by the $f_{cm}/f_{c,tf}$ ratio. This ratio averages 7.5 for RPC compositions (Table 4). For conventional high-strength fine-grained concretes this ratio is 10–11 [43]. The specific cement use efficiency is 40–50 kg/MPa for flexural strength and 5.3–7.5 kg/MPa for compressive strength. Other authors have observed similar values of specific cement consumption, which are in the range of 30-55 kg/MPa for flexural strength and 4.5–8 kg/MPa for compressive strength [7, 10, 30].

As it is shown in Fig. 4, the addition of fibers to RPC significantly increases its flexural strength. When the steel fiber content reaches 120 kg/m$^3$ ($\mu$ = 1.54%), the flexural strength at 28 days increases by about 70%, depending on the RPC composition. At a content of 240 kg/m$^3$ ($\mu$ = 3.08%), the strength increases by more than 2.2 times.

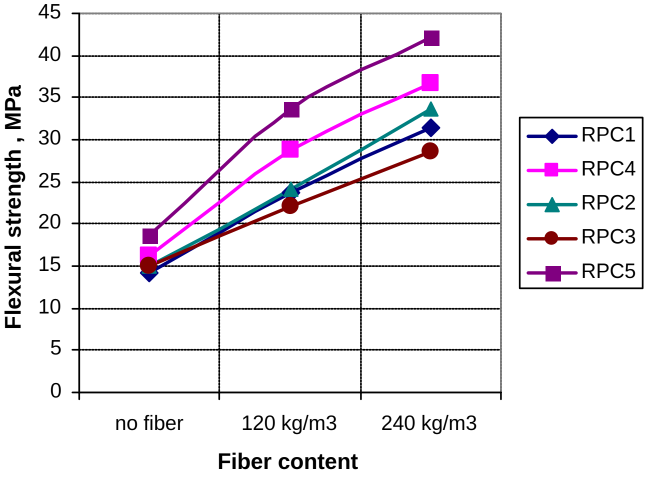

Fig. 4. Flexural strength of RPC with different fiber content at 28 days

It is known that the compressive strength of conventional fiber-reinforced concrete when using macrofiber (diameter 0.8–1 mm and more and a length of more than 40–50 mm) usually increases insignificantly compared to similar compositions of concrete without fibers [33]. In our case, at using microfiber a significant increase in strength was recorded. At a steel microfiber consumption rate of 120 kg/m$^3$, this increase was between 10–15%, and at a consumption rate of 240 kg/m$^3$, it was between 15–25%, depending on the composition of RPC (Tables 4–6). It is explained by the fact that the optimal structure of RPC, absence of coarse aggregate, and reduced geometric parameters of steel fiber can significantly increase fiber adhesion to the concrete matrix and create a ’framework’ in the concrete body. This has a positive effect on both flexural strength and compressive strength.

The flexural strength of the FRPC specimens at 1 day does not significantly differ from that of the RPC specimens (Fig. 5). This can be explained by weaker adhesion of the mortar part to the fiber in the early stages of hardening. Flexural strength values significantly increase at 7 days.

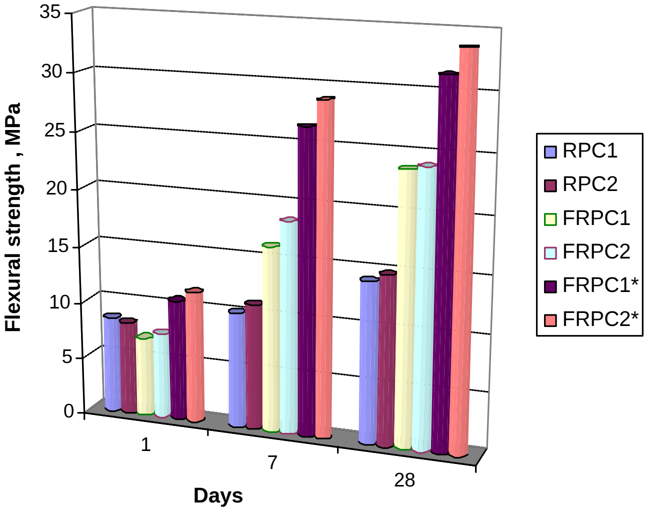

Fig. 5. Flexural strength growth kinetics for RPC and FRPC (Fiber consumption is 240 kg/m$^3$)

Note that the FRPC compressive strength varies depending on the type of active admixtures (Fig. 6).

The highest $f_{cm}$ values were obtained for specimens of FRPC5 composition. The maximum value of strength (162 MPa) was recorded at 28 days at a fiber consumption of 240 kg/m$^3$. In terms of strength, the RPFRC4 composition (containing metakaolin + fly ash) is practically not inferior to RPFRC5 (with silica fume). Fluctuations in strength depending on the composition averaged 25–30%. Increasing the fiber content from 120 to 240 kg/m$^3$ results in a 4–7% increase in compressive strength. It was found that the optimum value of the dispersed reinforcement content is in the range of 200–220 kg/m$^3$. A further increase in the fiber content in the concrete mixture can decrease its workability, requiring adjustments to water demand and addition of superplasticizer.

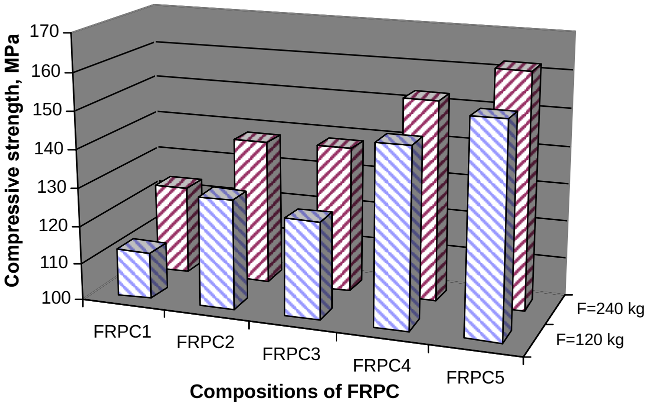

Fig. 6. Influence of FRPC composition on compressive strength at 28 days for various fiber contents

The flexural strength of RPC also depends on its composition (Fig. 7).

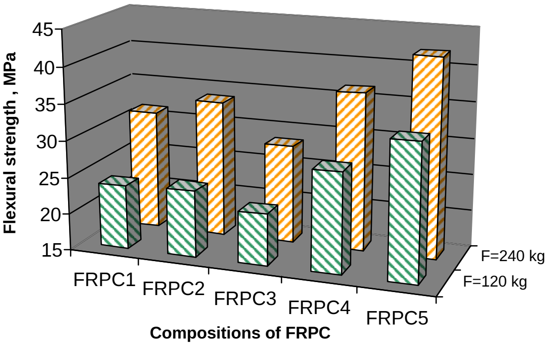

Fig. 7. Influence of FRPC composition on flexural strength at 28 days for different fiber consumption

The FRPC5 specimens containing silica fume and the FRPC4 ones containing metakaolin and fly ash showed the largest values of compressive and flexural strengths. An increase in flexural strength of 20-25% was observed when the fiber content was increased from 120 to 240 kg/m$^3$. Tables 4–5 show that the $f_{cm}/f_{c,tf}$ ratio for FRPC at both fiber contents is between 3.9 and 5.6, while for RPC it is between 7 and 8.1.

The specific cement use efficiency indicator in FRPC with the studied admixtures is 22–34 kg/MPa ($\mu$ = 1.54%) and 18-26 kg/MPa ($\mu$ = 3.08%), which is on average twice lower than for non-reinforced RPC. The efficiency indicator for compressive strength is 4.8–6.7 kg/MPa.

Figure 8 shows the ratio between fiber consumption and FRPC flexural strength (specific fiber consumption).

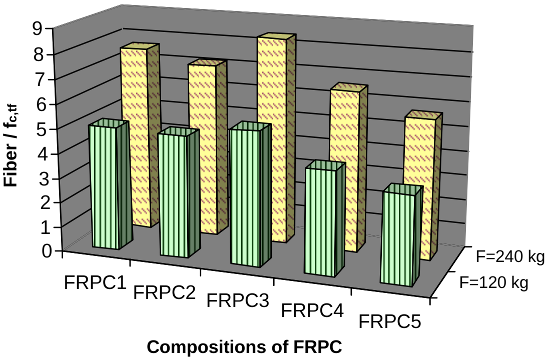

Fig. 8. The specific fiber consumption (specific efficiency of fiber use) per unit of FRPC flexural strength

It can be seen that increasing fiber consumption per 1 m$^3$ of concrete more than 120 kg does not result in a proportional increase in the value of specific fiber consumption per unit strength of fiber reinforced concrete.

To evaluate the economic efficiency of the proposed silica fume replacement by a complex admixture including metakaolin and fly ash the compositions of RPC4 and RPC5 (Table 3) were compared. For the same cement consumption and similar aggregate and superplasticizer consumption, these compositions differ in the admixtures used – silica fume for RPC5 and a complex admixture (metakaolin + fly ash) for RPC4. Assuming the cost of fly ash at 0.03 $/kg, metakaolin at 0.6 $/kg, and silica fume at 2 $/kg (the cost of silica fume depends on many factors and can reach 4 $/kg or even more) and the consumptions of the admixtures given in Table 2, the following cost of the components per 1 $m^3$ of concrete were obtained:

- silica fume – 224$,
- complex admixture – 53$.

Thus, neglecting other minor differences in the composition of RPC4 and RPC5 concrete, it can be noted that replacing silica fume with a complex admixture can decrease the cost of concrete at least by 171 per $m^3$ of concrete.

## 4. Conclusions

The present experimental study was aimed to evaluate the possibility of partial or complete replacement of silica fume in the RPC and FRPC composition with more available mineral admixtures. The key findings from the research are as follows:

1. It has been found that RPC and FRPC specimens containing silica fume and a composite admixture including metakaolin and fly ash showed compressive and flexural strengths that differ by 10-35% depending on the composition and age of curing.
2. RPC compositions containing fly ash and metakaolin achieved an average compressive strength of approximately 125 MPa and a flexural strength of over 16 MPa after 28 days. This is only a 20-35% reduction compared to concrete with silica fume.
3. Adding steel microfibers to the tested RPC compositions can increase compressive strength by 10-25%, depending on the composition.
4. With a steel fiber consumption of 240 kg/$m^3$, the FRPC flexural strength increases by 1.5 to 2.3 times, reaching 35 MPa.
5. The optimal content of microfiber in RPC is between 200 and 220 kg/$m^3$, as indicated by the strength values.

In summary, this study presents an innovative approach to use mineral admixtures in RPSC. The results allow to propose the use of a composite admixture containing fly ash and metakaolin as a replacement for high-cost silica fume, which in turn will lead to significant cost savings and higher construction efficiency.

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