Application of cementitious composites in mechanical engineering

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Abstract. The paper presents the results of the development of composite fiber-reinforced concrete for use as basic parts of machine-tools and machines. It was revealed that the additions of fly ash and limestone significantly reduce the cracking of concrete. Thus, a clear relationship between the properties of concrete and the features of the structure of cement stone was revealed. The strength and crack resistance of concrete is increased due to an increase in the number of low-basic calcium hydrosilicates, as well as increased gel porosity and reduced capillary porosity (especially at the submicroscopic level).

1. Introduction

Concrete finds application in mechanical engineering, where basic parts of machine tools, presses and other equipment and even hydraulic cylinders (hydraulic presses) are made of it. Due to the use of reinforced concrete in metal-intensive structures of heavy engineering, it is possible to obtain great savings in metal and significantly reduce the cost of structures. In addition, this makes it possible to liberate heavy engineering plants from the manufacture of large-sized products, processing and transporting of which in a number of cases present great difficulties. It should be noted that reinforced concrete frames absorb vibration better than cast iron. In particular, for the construction of large-sized autoclaves, in addition to steel, prestressed reinforced concrete can be used, which provides sufficient strength, crack resistance and rigidity of the autoclave body.

In this case, the size and shape of reinforced concrete structures of machines differ from construction products. For example, for press-forging machines with basic parts made of reinforced concrete, a frame is expediently made in the form of a hollow cylinder with thick bottoms, made of reinforced concrete with prestressed reinforcement. In this case, the pressing force developed by the mechanical components of the press is perceived by the prestressed reinforced concrete structure of the frame. With the use of high-strength concrete and reinforcement with a high tensile strength, the minimum dimensions and low weight of the press can be ensured [1-3].

Stability of the work of reinforced concrete elements of machine tools is determined mainly by two factors: shrinkage deformations and rigidity of fixing in concrete of various metal embedded parts through which operational loads are transferred. The metal insert part consists of an embedded plate
and an anchoring device providing its attachment to the concrete. The embedded plate has longitudinal and transverse ribs, which ensure its rigidity both during transportation and machining, and during the operation of the machine [3-4].

Compared with reinforced concrete structures used in the construction industry, concrete structures in engineering should be additionally calculated for a number of specific loads. In particular, when calculating the concrete structures of machines, the engineer is faced with the task of taking into account the effects of a repetitively repeated load. This account is reduced to assessing the endurance of structures, as well as to assess the change in elastic and residual deformations in them.

At the same time, the study of the limit of endurance of prestressed reinforced concrete elements showed the following:

1. The load causing stress from fatigue is always higher than the load causing the appearance of cracks.
2. If the repeatedly repeated load is less than the load causing the crack opening, no matter how large the number of loads, the load bearing capacity is not exhausted.

The disadvantages of concrete are the low tensile strength, the possibility of corrosion, the change in properties over time. These disadvantages can be partially minimized due to the composition, proper reinforcement, and also the filling technology.

2. Materials and methods

The development of high-strength fiber-reinforced concrete was carried out at the Far Eastern Federal University in cooperation with the Belgorod Technological University named after V.G. Shukhov [5-10]. As a result of the research, the optimal raw material components were selected for the further development of composite binder compositions on the basis of which high-efficiency fiber-reinforced concrete will be obtained. In particular, Portland cement CEM I 42.5, fly ash of CHP (Figure 1), limestone crushing waste, and PANTARHIT PC 160 hyperplasticizer were used to make the composite binder. As a filler, fractionated crushing of the Granite crushed stone of the Wranglevsky deposit enriched with sand of the Razdolnensky deposit was used. For disperse reinforcement, steel fiber was used.

![Figure 1. Typical particle shape of fly ash](image)

The manufacture of concrete was carried out as follows. The components of the composite binder
were co-grinded in a vario-planetary mill in the proportions: Portland cement 55 wt. %, fly ash - 40 wt. %, limestone crushing waste - 5 wt. %, hyperplasticizer 0.3 wt. %. Grinding was carried out for one hour to a specific surface of 550 m$^2$/kg.

In a vario-planetary mill, the rotational speeds of the grinding jars and the support disc can be set independently of one another. By varying the gear ratio, the movement and trajectory of grinding balls can be influenced so that the balls strike horizontally on the inner wall of the grinding jar (high impact energy), approach tangentially (high friction) or simply roll over the inner wall of the grinding jar (centrifugal mills). All intermediate stages and combinations between pressure friction and impact can be freely installed (Figure 2). Accordingly, grinding by vario-planetary mills is more energy-efficient than by ball mills and vibrating mills. In addition, due to the joint action of shock, centrifugal shock and abrasive forces, it becomes possible to achieve more highly disperse powders.

![Figure 2. Schematic operating principle of a vario-planetary mill.](image)

Joint grinding of cement, hyperplasticizer, ash and limestone promotes intensification of hydration processes during hardening. This allows to increase the activity of the composite binder to 62% in comparison with the control sample (CEM I 42.5). Despite the lowered values of the standard consistency of the raw mix of composite binder during hardening, there is a positive dynamics in the growth of physicomechanical parameters. So, the strength of cement stone on the developed composite binder (47.2 MPa) at the age of 3 days of natural hardening is 2 times higher than the strength of control samples, and in later terms - by 1.4-1.6 times. Joint grinding of the components not only leads to an increase in the ultimate compressive strength, but also to an increase in the speed of the strength of the samples on the composite binder.

3. Properties of the developed composite material

It has been established that the combined effect of mechanical and chemical activation (the presence of limestone particles) contributes to an increase in the pozzolanic activity of acidic ash. Analysis of the microstructure showed that ash and limestone particles are surrounded by gel formations. Individual particles are linked together, forming clusters. In such a cement stone is characterized by the presence of needle hydrosilicate neoplasms, whose length is 2 µm, and a diameter of about 0.2 µm (Figure 3).

By varying the percentage of the introduced ash, it is possible to control the amount and size of the ettringite crystals, which further determines the properties of the cements and concretes. Carbonates also have tight contacts with cement stone, which is explained by the appearance of epitoxic bonds between the cement products of hydration and limestone.

Thus, the addition of finely ground limestone is a chemical factor in increasing the activity of ash and sand interaction. It has a catalytic effect on the reaction activity of ash and sand surface during machining in a vario-planetary mill. The introduction of mineral additives in the initial binder
activates the hydration process. As a part of the hydration products of composite binder, the crystalline phases are redistributed of non-hydrated clinker minerals (C₃S, C₂S, C₄AF), quartz and calcite as well as hydration products (CH-Portlandite, 3C₃A·3CaSO₄·32H₂O-ettringite).

![Figure 3. The microstructure of neoplasms: a – cement stone without additives; b – cement stone based on the composite binder](image)

The model of the developed composite material is schematically represented in Figure 4.

![Figure 4. The model of the developed composite material](image)

In the production of concrete with improved mechanical characteristics, special attention must be paid to the choice of aggregates (quality, size, morphology of the grain surface), which play an important role in the production of concretes with high physical and mechanical properties. The increase in the size of aggregates entails, respectively, an increase in the concentration of stresses in the concrete body. Small aggregates give a more uniform structure, but increase the consumption of the binder. The larger the aggregate, the more concrete is prone to cracking, but at the same time a more rigid frame is created, which is important for reducing concrete deformation under load.

The structure-forming role of the aggregate is most pronounced when the surface of the interaction increases, these conditions are realized in fine-grained concretes with the use of screening of the granite crushed stone of the Vrangelovskoye deposit on the basis of composite astringents which, due
to the highly developed surface, allow intensifying the processes of structure formation and accelerate the strengthening of concrete, as well as the dense of structure.

To research the effect of composite binder on the properties of fine-grained concrete (gas, water and vapor permeability), samples of concrete were prepared with a slump flow within 10-12 cm on the developed composite binders, which were further investigated for various technological parameters normalized during construction.

Investigation of the physical and mechanical properties of fine-grained concrete (Table 1) showed that the use of composite binder, obtained by joint grinding of cement, fly ash, limestone and hyperplasticizer, allows to increase the technical characteristics of concrete, in comparison with similar compositions manufactured using traditional binding materials. This fact is explained by the denser structure of the cement stone on the developed composite binder, with a lower porosity, due to less water in the concrete. The best physical and mechanical characteristics showed compositions No. 1 and No. 2 (cement - 51-59 wt. %, acidic ash - 36-44 wt. %, limestone - 4-9 wt. %). It should be noted that increasing the amount of ash and reducing the amount of cement to ensure equi-mobility of the compositions (slump flow is 10-12 cm), it is necessary to increase the amount of mixing water introduced into the concrete mixture.

Despite a number of advantages in comparison, for example, with conventional heavy concrete, fine-grained concrete is characterized by high shrinkage and a modulus of elasticity reduced by 20-25%.

| Composition number | Consumption of materials per 1 m³ | Compres- sive strength, MPa | Prism strength, MPa | Elastic modulus, GPa |
|-------------------|----------------------------------|---------------------------|--------------------|--------------------|
|                  | Cement, kg | Fly ash, kg | Limestone, kg | Hyperplasticizer, kg | Screening of crushed stone, kg | Sand, kg | Water, l | Slump flow, cm | 10-12 |
| 1*               | 550        | -          | -            | 220                | 107.5               | 86.3     | 61.2     |
| 2                | 288        | 235        | 27           | 240                | 83.7                | 59.5     | 43.8     |
| 3                | 275        | 246        | 29           | 241                | 84.2                | 60.3     | 44.5     |
| 4                | 257        | 257        | 36           | 242                | 76.3                | 55.2     | 40.9     |
| 5                | 244        | 268        | 38           | 243                | 75.2                | 55.0     | 40.8     |
| 6                | 230        | 278        | 42           | 244                | 75.0                | 54.9     | 40.8     |
| 7**              | 550        | -          | -            | 215                | 63.1                | 42.3     | 36.2     |

* The binder is obtained by co-grinding the components up to Ssp = 550 m² / kg
** Astringent on the basis of Portland cement produced by JSC "Spasskcement" (without regrinding)

Great opportunities to increase performance characteristics are opened by the dispersive reinforcement of fine-grained concrete by polymer and metal fibers. In order to obtain high density fibrous concrete, the effect of introducing reinforcing fibers into the concrete matrix was studied. As a basis for the concrete matrix, the composition No. 3 was adopted according to Table. 1.

To determine the optimal percentage of reinforcement of fine-grained steel-fiber-reinforced concrete, samples of concrete of the same composition with different content of steel fiber were molded (Table 2). It is established that at 1.4-1.6% of reinforcement by volume, it is possible to obtain the maximum physico-mechanical parameters. Further increase in the percentage of reinforcement is impractical, since it causes a decrease in the strength and performance characteristics of fiber-reinforced concrete.

Also, studies were conducted on reinforcing the developed concrete with basalt fiber. However, the
results from the tests showed that reinforcement with steel fiber gives better physical and mechanical characteristics of the concrete.

Table 2. Dependence of the strength of fine-grained fibro-concrete on the percentage of reinforcement

| Composition number | Consumption of materials per 1 m³ | Percentage of reinforcement, % | Rc, MPa |
|--------------------|----------------------------------|--------------------------------|---------|
| 3-1*               | Binder 550 | Water 240 | Aggregate 1623 | Fiber - | 0 | 94.2 |
| 3-2                | 550 | 240 | 1623 | 23.97 | 1 | 96.1 |
| 3-3                | 550 | 240 | 1623 | 28.76 | 1.2 | 97.3 |
| 3-4                | 550 | 240 | 1623 | 33.56 | 1.4 | 99.8 |
| 3-5                | 550 | 240 | 1623 | 38.35 | 1.6 | 100.9 |
| 3-6                | 550 | 240 | 1623 | 43.15 | 1.8 | 99.5 |
| 3-7                | 550 | 240 | 1623 | 47.94 | 2 | 99.6 |

* The control composition corresponds to composition No. 3 (Table No. 1)

4. Conclusion
The compositions of fiber-reinforced concrete on composite binder, using raw materials of Primorsky Krai, have been developed. When reinforcing concrete with steel anchor fiber in an amount of 1.6% by volume, it is possible to obtain the maximum physical and mechanical parameters - Rc = 100.9 MPa.

It was revealed that the additions of fly ash and limestone significantly reduce the cracking of concrete. Thus, a clear relationship between the properties of concrete and the features of the structure of cement stone is revealed. The strength and crack resistance of concrete is increased due to the increase in the number of low-basic calcium hydroxides, as well as increased gel porosity and reduced capillary porosity (especially at the submicroscopic level).

The developed composition of concrete can find application in mechanical engineering, where basic parts of machine tools, presses and other equipment, hydraulic cylinders (hydraulic presses) and autoclaves are made from it.

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