Influence of Silicon-Containing Additives on Concrete Waterproofness Property

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Abstract. The article studies the influence of silicon-containing additives on the property of the water resistance of concrete samples. It provides a review of the literature on common approaches and technologies improving concrete waterproofness and reinforced concrete structures. Normal hardening samples were obtained on the basis of concretes containing microsilica, aerosil or ash, or the combinations thereof. This research is aimed at the study of the complex modifier effect on the basis of metakaolin, superplasticizer and silicon containing additives on the property of concrete water resistance. The need to use a superplasticizer to reduce the water-cement ratio and metakaolin as a hardening accelerator along with the set of strength is substantiated. This article describes a part of the results of the experiment conducted to find alternative options for colmatizing expensive additives used in the concreting foundations of private house-building. The implementation of the scientific work will not only clarify this area but will also broaden the knowledge of such additive as aerosol.

1. Introduction
These Modern construction is inconceivable without the "material of the 20th century" - concrete, which firmly holds the place of the main structural material and, despite the appearance of new efficient materials and structures, will retain its leading position for many years to come.

At the moment, heavy concrete is the most commercially available building material. It has become of such a wide use due to its ability to maintain its qualities, being influenced by chemical media and exposure to physical activity. In its turn, the composition and structure of the artificial stone make up its future range of properties.

One of the key factors affecting the longevity of underground and deeper parts of buildings and structures is the effect of water. The water penetrating into the building structures causes corrosion of the reinforcement and destruction of the concrete, which leads to a decrease in the structural properties and, as a result, causes complete destruction of the material. With the assumption of water penetration into the interior of the underground part of buildings, their operational qualities decrease and leading to disruption of the technological equipment, worsening the microclimate of the premises, etc.

According to various studies, about 90% of buried and subterranean structures have problems with waterproofing, which are already manifested at an early stage of operation and lead to accelerated wear of load-bearing structures.
Most of the problems in the work of waterproofing are associated with the choice of inadequate or incorrect for this case technological solutions. To reduce the risks of these problems, it is necessary and important to choose the right technological solutions for waterproofing, which contribute to the almost complete elimination of water leakage, and also reduce the potential cost of restoration of waterproofing. Waterproofing system provides for:

- protection of the underground part of the structure against water penetration
- protection of the underground parts of the structures from wetting by underground waters
- possibility to operate the underground parts of the structures with minimum expenses for their maintenance and practically without restrictions
- protection of the life support system, engineering equipment and communications
- resistance to the impact on the underground part of the static and dynamic structures of underground and surface water [1].

Permeability of concrete is a property of concrete to pass through itself gases or liquids in the presence of a pressure gradient (governed by the brand for waterproofness W) [2].

For the construction of foundations, hydraulic structures and a number of others one of the main characteristics is their permeability. This property in the known way is to determine the ability of the material to resist the processes of freezing-thawing, moistening and drying, as well as the effects of the atmosphere and aggressive environments. In practice, the most important is the waterproofness of concrete. Penetration into the thickness of concrete, according to the studies of A.M. Neville, V.M. Moskvin, F.M. Ivanov, S.N. Alekseev, E.A. Guzeev [3,4], affects its longevity, for example, washout of calcium hydroxide or action of aggressive solutions and media.

Concrete is a capillary porous material, an integral part of which is a network of thinnest pores and capillaries of various sizes. Small pores (micropores) of less than 10-5 cm in size are practically impermeable to water. In the main it is the pores of the cement gel. Capillaries and macropores of a larger size do not interfere with water filtration, resulting from pressure, osmotic pressure, or moisture gradients. Therefore, the permeability of concrete to a straight line correlates with the volume of micropores of capillaries in concrete [5].

The volume of macropores in concrete can be from 0 to 40% of the total. Decrease in water-cement ratio, reduction of air entrainment, increase in the degree of hydration of cement, and also introduction of various additives allow to lower macroporesity [6]. Figure 1 visually demonstrates the relationship between permeability and the water-cement ratio [7].

![Figure 1](image)

**Figure 1.** Dependence of the coefficient of permeability of concrete $K_{pr}$ on the water-cement ratio.

In real conditions, it is possible to trace a significant deviation from these dependencies, since the process of creating concrete involves many factors, for example, the degree of compaction that can significantly affect the permeability of concrete.

Microcapillaries filled with water create the so-called pore and capillary colmatizing effect, which reduces the permeability of concrete [8].

With the increasing age of concrete, the degree of hydration of cement increases and as a result the volume of micropores decreases, as a result of which the permeability of concrete decreases.

The permeability of concrete is also affected by the aggregate. The greater its open porosity, the less waterproof it will have concrete [3].

To increase the impermeability of concrete the special methods, given in Table 1 are applied.
Using special additives or substances in the course of concrete production is relatively easy effective measures to increase waterproofness. Various kinds of surfactants, water-soluble resins, emulsions (for example, bitumen), water-repelling silicone fluid (WRSF) and other methods are well studied and tested by time [9,10].

**Table 1. Methods and degree of lowering the permeability of concrete.**

| Method                                                      | Degree of lowering, times |
|-------------------------------------------------------------|----------------------------|
| Introduction of organic and hydrophobic additives to the concrete mixture | 2-10                      |
| Introduction of inorganic additives to the concrete mixture | 5-1000                    |
| Introduction of thickening agents or thermoplastic polymers into the concrete mixture | 10-500                    |
| Impregnation with special substances after manufacturing    | 50-1000                   |
| Hydrophobization of surface layers of concrete              | 2-10                      |
| Coating with special film-forming compounds                 | 10-100                    |
| Impregnation with a monomer followed by polymerization      | 50-1000                   |

Sometimes thin-powdered powders of polymeric substances or similar to them, for example, pecks are used [11,12]. Good water resistance values are obtained with the use of complex additives or special astringents with non-shrinking or expanding properties.

Impregnation of concrete with sulfur, liquid glass, paraffin, petrolatum makes it possible to well cushion capillaries and pores [13]. Mechanical methods can also be used, for example, pressing.

Among the additives used in concrete technology, two large groups occupy a special place - active mineral additives (AMD) and additives-plasticizers. The use of highly effective AMD contributes to the strength, resistance to chemical and frost aggression and savings in cement in the production of concrete [14]. According to the researches of E. Gamaliy, B. Trofimov, L. Kramar and others it is known that the use of microsilica gives a cement matrix with high density and water resistance, promotes acceleration of hydration of clinker minerals, leads to formation of stable high-strength structures in low-basic calcium hydroxylates in cement stone [8,15-18].

The influence of introducing fine-dispersed systems, including microsilica, was studied by A. Brykov, M. Voronkov, and M. Mokeev. [9].

However, this issue has not been fully studied and is of scientific interest.

Based on the literature review, the following goal was set: to investigate the effect of microsilica and aerosil additives on impermeability of concrete.

2. **Experimental data.**

For preliminary tests, sandy concrete of a composition of 1:3 was used, with a consistency of normal density.

As components of the binder, TsEM II/ A-Sh 42,5H ООО "Dyckerhoff Korkino cement", microsilica of the Chelyabinsk Electrometallurgical Combine of the brand MKU-85, aerosil of the brand "380" from "Evonik Degussa GmbH", superplasticizer C-3 were used.

To accomplish the task, a two-factor experiment was implemented in the laboratory, and the variable factors were the amount of AMD (microsilica or aerosil), (factor X) and superplasticizer (factor Y). The analysis of the results obtained during the experiments included the mathematical processing of the results of the study in order to obtain the values of a polynomial of the second degree. The plan-matrix experiments with aerosil and MKU and their results are presented in Tables 2, 3 and 4, 5 respectively.

According to the results of the experiment presented in Table 3, it is obvious that introduction of aerosil at a rate of 3% instead of cement markedly reduces strength, therefore, for the following experiments, it was decided to use a replacement for the aerosilizing agent by 1.5%.
Table 2. Plan-matrix experiment with the addition of aerosol.

| Composition number | AMD content | SP content |
|--------------------|-------------|------------|
|                    | Code value  | B %        | Code value | B % |
| 1                  | 0           | 0         | -1         | 0,8 |
| 2                  | 0           | 0         | 0          | 0,9 |
| 3                  | 0           | 1,5       | +1         | 1   |
| 4                  | 0           | 1,5       | -1         | 0,8 |
| 5                  | 0           | 1,5       | 0          | 0,9 |
| 6                  | 0           | 1,5       | +1         | 1   |
| 7                  | +1          | 3         | -1         | 0,8 |
| 8                  | +1          | 3         | 0          | 0,9 |
| 9                  | +1          | 3         | +1         | 1   |

Table 3. Results of the experiment with the addition of aerosol.

| Composition number | Normal consistency, HK % | Flexural strength at different hardening times, MPa | Compressive strength at different hardening times, MPa |
|--------------------|--------------------------|-----------------------------------------------------|------------------------------------------------------|
|                    |                          | 1          | 7         | 28        | 1          | 7         | 28        |
| 1                  | 38,8                     | 2,01      | 6,10      | 7,56      | 10,1       | 31,4      | 45,6      |
| 2                  | 37,5                     | 2,35      | 6,88      | 7,68      | 11,2       | 32,0      | 49,6      |
| 3                  | 36,3                     | 2,89      | 6,90      | 8,48      | 12,8       | 35,4      | 58,6      |
| 4                  | 45,7                     | 2,28      | 5,81      | 6,85      | 12,0       | 26,1      | 37,0      |
| 5                  | 43,1                     | 2,75      | 6,53      | 7,23      | 14,1       | 32,6      | 39,9      |
| 6                  | 43,1                     | 3,79      | 6,78      | 7,91      | 15,9       | 34,9      | 41,6      |
| 7                  | 58,0                     | 2,63      | 4,40      | 5,65      | 8,4        | 23,5      | 29,1      |
| 8                  | 54,1                     | 2,75      | 4,98      | 5,80      | 8,8        | 24,3      | 30,0      |
| 9                  | 52,8                     | 2,83      | 5,15      | 5,93      | 9,9        | 26,1      | 33,7      |

Table 4. Experimental plan-matrix with microsilica.

| Composition number | AMD content | SP content |
|--------------------|-------------|------------|
|                    | Code value  | B %        | Code value | B % |
| 1                  | 0           | 0         | -1         | 0,8 |
| 2                  | 0           | 0         | 0          | 0,9 |
| 3                  | 0           | 1,5       | +1         | 1   |
| 4                  | 0           | 4         | -1         | 0,8 |
| 5                  | 0           | 4         | 0          | 0,9 |
| 6                  | 0           | 4         | +1         | 1   |
| 7                  | +1          | 8         | -1         | 0,8 |
| 8                  | +1          | 8         | 0          | 0,9 |
| 9                  | +1          | 8         | +1         | 1   |

The responses from Table 5 make it possible to draw an unambiguous conclusion that the best indicators are compositions where 8% of the mass of the astringent was replaced with microsilica. And for further experiments this dosage will be used.

After molding, the samples (40x40x160mm) were stored for 28 days under normal hardening conditions.
In cases with both aerosil and microsilica, the lowest values of the normal consistency were obtained by introducing 1% superplasticizer, and these compositions had the lowest W/C ratio in the series. As it was pointed out in the literature review of this article, the smaller the W/C ratio, the less the permeability of concrete, which is what must be achieved during this research.

Based on the results of the mathematical method of planning [19], the regression equations of the following type were obtained:

\[ M(x,y) = b_0 + b_1 x + b_2 y + b_{11} x_2 + b_{22} y_2 + b_{12} x_2 y_2 \]  \hspace{1cm} (1)

where \( b_0, b_1, b_2, b_{11}, b_{22}, b_{12} \) – coefficients of the regression equation; \( x, y \) – variable factors.

The values of coefficients \( b_0, b_1, b_2, b_{11}, b_{22}, b_{12} \) and Fisher (FR) for two-factor experiments are presented in Table 6.

### Table 5. Results of the experiment with the addition of microsilica.

| Composition number | Normal consistency, HK % | Flexural strength at different hardening times, MPa | Compressive strength at different hardening times, MPa |
|--------------------|--------------------------|---------------------------------------------------|----------------------------------------------------|
|                    | 1  | 7  | 28 | 1  | 7  | 28 | 1  | 7  | 28 |
| 1                  | 38,8 | 2.01 | 6.10 | 7.56 | 10.1 | 31.4 | 45.6 |
| 2                  | 37.5 | 2.35 | 6.88 | 7.68 | 11.2 | 32.0 | 49.6 |
| 3                  | 36.3 | 2.89 | 6.90 | 8.48 | 12.8 | 35.4 | 58.6 |
| 4                  | 45.1 | 2.12 | 7.59 | 9.91 | 17.1 | 27.3 | 50.3 |
| 5                  | 44.0 | 2.43 | 7.70 | 10.3 | 19.2 | 29.1 | 51.4 |
| 6                  | 42.2 | 2.59 | 7.96 | 10.4 | 20.0 | 31.3 | 54.5 |
| 7                  | 48.3 | 2.57 | 8.44 | 10.59 | 21.4 | 35.7 | 57.5 |
| 8                  | 47.1 | 2.73 | 8.87 | 10.69 | 23.1 | 39.6 | 63.6 |
| 9                  | 45.9 | 2.81 | 8.94 | 11.0 | 24.5 | 41.5 | 64.1 |

### Table 6. Values of coefficients of regression equations and Fisher.

| AMD | Coefficients | Value of the coefficients in determining the flexural strength at various time of hardening | Value of the coefficients in determining the compressive strength at various time of hardening | Value of the coefficients in determining (HK) |
|-----|--------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|---------------------------------------------|
|     |              | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days |
| aerosil | \( b_0 \) | 2,859 | 6,555 | 7,223 | 13,900 | 31,244 | 38,767 | 29,569 |
|  | \( b_1 \) | 0,432 | 0,420 | 0,377 | 1,350 | 2,257 | 3,700 | 2,748 |
|  | \( b_2 \) | 0,160 | -0,892 | -1,057 | -1,167 | -4,150 | -10,167 | -0,321 |
|  | \( b_{11} \) | 0,122 | -0,273 | 0,160 | 0,150 | -0,067 | 1,100 | 0,459 |
|  | \( b_{12} \) | -0,170 | -0,013 | -0,160 | -0,300 | -0,350 | -2,100 | -0,250 |
|  | \( b_{22} \) | -0,363 | -0,638 | -0,480 | -3,800 | -2,417 | 1,600 | -1,043 |
|  | FR | 98,603 | 6,958 | 31,848 | 3,352 | 41,394 | 26,209 | 34,719 |
| MKU | \( b_0 \) | 2,383 | 7,858 | 10,137 | 18,889 | 29,100 | 51,911 | 28,006 |
|  | \( b_1 \) | 0,265 | 0,278 | 0,303 | 1,450 | 2,300 | 3,967 | 4,412 |
|  | \( b_2 \) | 0,143 | 1,062 | 1,427 | 5,817 | 3,000 | 5,233 | 4,501 |
|  | \( b_{11} \) | -0,005 | -0,162 | -0,100 | -0,183 | 0,200 | 0,233 | -0,067 |
|  | \( b_{12} \) | -0,160 | -0,075 | -0,128 | -0,100 | 0,450 | -1,600 | -0,281 |
|  | \( b_{22} \) | 0,180 | -0,062 | -0,870 | 1,583 | 6,700 | 4,433 | 5,524 |
|  | FR | 4,038 | 27,279 | 25,326 | 0,775 | 6,257 | 58,298 | 14,105 |
After analyzing the results of preliminary experiments, it was decided that the following dosages of the components would be used to study the waterroofness of concretes: aerosil: 0.2, 0.8 and 1.5%, microsilica 6 and 8%, superplasticizer C-3 - 1%. Additional formulations with aerosil dosages of 0.2 and 0.8% by weight of cement were introduced in order to study the dosage area of the aerosil additive of less than 1.5%. Also, metakaolin (MTK) of the firm "Plast Rifei" and fly ash from coal combustion at Reftinskaya GRES were additionally applied. Their dosages in the amount of 2.5% and 6%, respectively, were taken according to the studies conducted at the Department of Construction Materials of SUSU, Chelyabinsk, by A.A. Kirsanova and other investigators.

The decision to apply metakaolin is justified by the fact that on the scale of the whole work the study touches on the problems of concreting foundations of private house-building, where the construction period is short, especially in the conditions of Siberia and the Urals. And the use of fly ash in small dosages will reduce the cost of the concrete mixture. The projected compositions are presented in Table 7.

The strength and water-permeability responses were obtained on the test compositions and are summarized in Table 8.

According to the data presented in Table 8, the optimal results for compressive strength and water resistance indicators were obtained in composition No. 1. This again confirms earlier studies on the use of microsilica in concrete as a modifier of its structure, and proves that introduction of microsilica into the composition of concrete leads to the formation of low-basic calcium hydrosilicates of a layered structure that increase water impermeability and other properties of the material. Composition No. 5 was taken from literature sources and is given for comparison [8].

Table 7. Compositions of concrete mixtures used per 1 m³.

| Composition number | Cement, kg | Sand, kg | Crushed stone, kg | Water, kg | C-3, kg | MKU, kg | Aerosil, kg | Ash, kg | MTK, kg |
|--------------------|------------|----------|------------------|-----------|---------|---------|------------|---------|--------|
| 1                  | 322        | 850      | 1150             | 136       | 3,5     | 28      | 0          | 0       | 8,05   |
| 2                  | 344,75     | 850      | 1150             | 136       | 3,5     | 0       | 5,25       | 0       | 8,05   |
| 3                  | 347,2      | 850      | 1150             | 136       | 3,5     | 0       | 2,8        | 0       | 8,05   |
| 4                  | 349,3      | 850      | 1150             | 136       | 3,5     | 0       | 0,7        | 0       | 8,05   |
| 5                  | 308        | 850      | 1150             | 136       | 3,5     | 21      | 0          | 21      | 8,05   |
| 6                  | 350        | 850      | 1150             | 136       | 3,5     | 0       | 0          | 0       | 8,05   |

Table 8. Values of strength and waterproofness Limits.

| Composition number | Compressive strength at various time of hardening, MPa | Water resistance, class W |
|--------------------|-------------------------------------------------------|--------------------------|
|                    | 1 day | 3 days | 7 days | 28 days |                         |                         |
| 1                  | 18,94 | 30,00  | 27,87  | 61,28   | 16                      |                         |
| 2                  | 12,13 | 21,29  | 31,09  | 47,42   | 18                      |                         |
| 3                  | 24,24 | 29,11  | 34,60  | 42,48   | 14                      |                         |
| 4                  | 24,07 | 28,24  | 34,26  | 44,95   | 10                      |                         |
| 5                  | 17,44 | 23,82  | 32,79  | 49,47   | 20                      |                         |
| 6                  | 22,81 | 27,15  | 31,03  | 40,49   | 4                       |                         |

According to the data presented in Table 8, the optimal results for compressive strength and water resistance indicators were obtained in composition No. 1. This again confirms earlier studies on the use of microsilica in concrete as a modifier of its structure, and proves that introduction of microsilica into the composition of concrete leads to the formation of low-basic calcium hydrosilicates of a layered structure that increase water impermeability and other properties of the material. Composition No. 5 was taken from literature sources and is given for comparison [8].
According to the results of the experiments carried out on compositions 2, 3 and 4 with the addition of aerosil, it can be concluded that aerosil does not interact with Ca(OH)$_2$ concrete, that is, it does not form compounds like those obtained in the interaction of microsilica with Ca(OH)$_2$. This means that the increase in water resistance with increasing the dosage of aerosil occurs only due to the compaction of the structure of concrete itself by pore colmatation. This position is proved by the results of the derivatographic analysis (DT), presented in Figures 1 and 2 [19].

![Figure 2. DT analysis of composition No. 2.]

![Figure 3. DT analysis of composition No. 4.]

3. Conclusions

Based on the data obtained, it can be concluded that sealing the structure and increasing the waterproofness of concrete by introducing microsilica or microsilica with ash is effective and expedient. And using aerosil to obtain similar properties for waterproofness is not justified, since its price is much higher than that of compositions with microsilica and ash. And also, the hydrosilicates formed during the interaction of MKU with calcium hydroxide are more durable and stable, due to
their low basicity and amorphous weakly crystallized structure. Therefore, these compositions can be recommended for concreting foundations of private housing construction.

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