Development of Flat Roof Construction with Waterproofing from Modified Self-Compacting Concrete

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Abstract. The given article considers the issues of increase of building flat roof durability by application of the modified self-compacting concrete (SSC). When SSC was modified, a complex modifier was developed and the optimization of the complex modifier composition was carried out using a three-factor experiment. The physico-mechanical properties of the obtained SSC are determined. The microstructure and phase composition of the modified cement stone were studied. On the basis of the studies carried out, namely, X-ray phase analysis and electron microscopy, it was concluded that the reduced content of calcium hydroxide in the samples with a complex modifier is due to the adsorption of calcium hydroxide on highly dispersed particles and the reaction of interaction with metakaolin also contributing to reduction in the content of calcium hydroxide in cement stone. The received data allow one to speak about SSC high operational characteristics. With the mark for the spreading of cone P5, the modified SSC has a class of compressive strength B50, high frost resistance (F600) and water resistance (W16).

1. Introduction

Flat roofs are wide-spread both in civil and industrial construction. The bituminous mastic and blanket insulation are used as a waterproofing layer of such kinds of roofs, but these materials have low strength, fireproof and longevity. PolyVinylChloride membranes, thermoplastic polyolefin and ethylene propylene diene monomer are also implemented at the present time [1,2]. Such kind of underlay has a long service lifetime (no less than 50 years), but there are the special conditions for its using: the protection against transferring the flammables, asphalt flux and the protection from mechanic damage of membranes are necessary; the movement on the roof at a temperature below -15˚С is not allowed; the performance monitoring of roof drainage system is necessary; the movement on the roof is permitted only by the special pedestrian precincts; snow plowing is allowed only by the special wooden shovels, moreover, it’s necessary to leave the safety lay of snow of size of 10 cm [3].

One of the ways of load-bearing and durable underlay production is the way of using the concrete as a waterproofing layer.

The experience of using roofs made with heavy-weight concrete slabs is widely known [4,5]. There had been built over 3 million sq.metres of reinforced-concrete non-roll roofing in Novosibirsk, Ekaterinburg and other cities since 1980. For over 30 years of monitoring these kinds of roofs confirmed their high performance characteristic and degree of reliability [4]. However, towards the
end of 1980s there was the cease of using such kind of roofs in view of the reduction of factory-built housing and the increase of unusual house-building with the use of monolithic construction.

One of the solving of this problem is the waterproofing layer made of modified self-compacting concrete (SCC) 30-40mm thick, what can help to use it as conventional design of flat roof. The technical novelty of this concept is proved true by Russian patent [6,7]. There is the structural features of the non-roll roofing in Figure 1.

The purpose of this study is the production and investigation of self-compacting concrete with high performance characteristics for waterproofing of the flat roofs of the buildings.

2. Materials and Methods of Research

The Portland cement CEM II/A-S (III-II) 32,5 R corresponding to Russian state standard GOST 31108-2003 “Cements. Technical conditions” EN 197-1:2000 produced by Ulyanovskcement LLC was used as a cementitious matter. The cement consists of the following main minerals: C3S – 57 %, C2S – 17 %, C3A – 7.5 %, C4AF – 12.8 % and admixtures: gauze – 9.1 %, SO3 – 2,36 %. The concrete sand with fineness modulus 2.79 and size of sand about 0.16-5 mm corresponding to Russian state standard GOST 8736-2014 was used as fine aggregate. The 5 to 10 mm grain size crushed stone corresponding to Russian state standard GOST 8267-93 was used as coarse aggregate.

In the research the following admixtures are used as modifying agents: superplasticizer (SP) Remicrete SP 10 produced by SCHOMBURG GmbH company (Germany) (admixture is compatible with PN-EN 934-2:T3.1 и 3.2), organosilicone hydrophobisator (HP) “Tiprom S” produced by “Proizvodstvennoe obedinenie “SAZI” LLC (TS 2229-069-32478306-2003). Metakaolin (MtK) was used as active mineral admixture – noncrystalline aluminium silicate occurrence in ZHeravlinyj Log (TS 5729-095-51460677-2009). In our study we used “Chelyabinka” fibre 36-38 mm length as dispersed reinforcement that was fabricated by rolled iron cutting in keeping with TS 1231-001-70832021-2010. X-ray patterns were measured on the automatic X-ray diffractometer D2 Phaser (manufacturing company Bruker AXS GmbH). Processing the received interference spectrums was made with the use of the DIFFRAC.SUITE software package. The diffractive database named ICDD PDF-2 Release 2013 helped to make the phase identification with the use of the DIFFRAC.EVA-v3.1 program module. The statement of amount of the phases was made by Rietveld method with the use of DIFFRAC.TOPAS-v4.2 program module.

Microstructure of cement stone was determined by means of a high-resolution autoemissive electronic scanning microscope Merlin produced by CARL ZEISS Company. The spalls of cement stone samples were mist by composite metal Au/Pd in the ratio 80/20 on the high-vacuum unit named Quorum T150 ES.
Concrete strength test was made for concrete test cubes with dimensions of 100x100x100mm according with Russian state standard GOST 10180-2012 “Concretes. Methods for strength determination using reference specimens”, and prisms with dimensions of 100x100x400mm were used for bending strength testing.

The freeze-thaw durability test was made by means of the second rapid test method with repeated freezing and frost retreat corresponding to Russian state standard GOST 10060-2012, the concrete shrinkage was determined corresponding to Russian state standard GOST 24544-81.

We carried out absorption test for SCC corresponding to Russian state standard GOST 12730-78. Watertightness of self-compacting concrete was determined corresponding to Russian state standard GOST 12730.5-84 “Concretes. Methods for determination of watertightness” and to annex 4 of this standard with the use of test cylinders in diameter 150 mm by means of the unit “AGAMA-2RM”.

Compounding properties were determined corresponding to Russian state standard GOST 10181-2014, and also by means of the methods, that reported in studies [8-10]. Critical stress intensity factor was determined corresponding to Russian state standard GOST 29167-91.

With the purpose of optimization the heavy-weight concrete’s composition with admixtures we used second-order three-factor hypercubic design that is inclined D-optimus with 6 points at the center of design and makes possible to explain the dependence as a second order polynomial.

3. Results and Discussion
The increase of the longevity of self-compacting concrete for flat roofs is impossible without development of complex modifying agent that consists of hydrophobisator and active mineral admixtures [11,12], the fiber reinforcement is also necessary for the crack resistance of concrete increase [13].

| Components                      | Consumption of components, kg / m³ |
|---------------------------------|-----------------------------------|
| Cement                          | 450                               |
| Sand fraction - 0.16-5 mm        | 572.5÷584.5                       |
| Sand fraction - 0.16-0.63 mm     | 286.5÷292.5                       |
| Crushed stone fraction 5-10 mm   | 905                               |
| SP                              | 5.4÷8.1                           |
| HP                              | 0.45÷0.9                          |
| MtK                             | 13.5÷31.5                         |
| Fibre                           | 39                                |
| Water                           | 180                               |

Experimental investigations of domestic and foreign water reducing admixes on rheological properties of cement-water paste were carried out in study [14], as a result there was found out the most effective one - superplasticizer (SP) Remicrete SP 10 based on polycarboxylic ethers. The influence of water soluble and water-insoluble silicone waters on properties of cement-water paste and mortar was learned, and the effective hydrophobisator Tiprom S was found out in the article [15]. The “Chelyabinka” fibre as fiber reinforcement and the active mineral admixture metakaolin were chosen as components of SCC in consequence of the carried out experimental investigations.

The optimization of the complex modifying agent composition was made on self-compacting concrete (the composition of concrete mixture is shown in Table 1) by means of the second-order three-factor hypercubic design.

The content of the basic independent variables was measured: superplasticizer – 1.2-1.8 %; hydrophobisator – 0.1-0.2 %; metakaolin – 3-7 % by weight of cement.

The concrete strength at 7 and 28 days (R₇, R₂₈) and freeze-thaw resistance (F) are chosen as achieved effects.
After the data reduction process of mathematic planning there are the following mathematical dependences:

\[ R_7 = -77.63 + 137.54X_1 + 137.46X_2 + 5.49X_3 + 105.16X_1X_2 + \\
+ X_1X_3 + 5.06X_2X_3 - 48.83X_1^2 - 1.11 \times 10^3X_2^2 - 0.71X_3^2 \] (1)

\[ R_{28} = -80.9 + 152.56X_1 + 194.65X_2 + 5.34X_3 + 54.52X_1X_2 + \\
+ X_1X_3 + 4.61X_2X_3 - 52.08X_1^2 - 1.059 \times 10^3X_2^2 - 0.76X_3^2 \] (2)

\[ F = -3.16 \times 10^3 + 3.159 \times 10^3X_1 + 1.073 \times 10^4X_2 + 196.24X_3 - 793.65X_1X_2 + \\
+ 19.84X_1X_3 + 119.05X_2X_3 - 1.041 \times 10^3X_1^2 - 3.076 \times 10^4X_2^2 - 23.43X_3^2 \] (3)

As you can see from the equations 1 and 2, the gain in strength can be observed while increasing the consumption of SP and MtK. The concrete strength at 7 days is reduced in the process of the increasing the water-repellent agent content. The concrete strength increases gradually with the increase of SP and MtK, MtK and HP gauging, and decreases after this. The strength reduction during the increase of SP and HP gauging can be explained by the blocking action of portland cement particles of this modifying agents, and it appears in a greater degree during the combined introduction of the both admixtures.

As you can see from the mathematical dependence (3), there is the increase of freeze-thaw resistance in the processes of increasing the SP gauging, HP gauging, and combined the SP and HP gauging.

Based on the mathematic planning the optimum gauging of the complex modifying agent components were determined: superplasticizer – 1.5%, hydrophobisator – 0.15%, metakaolin – 5% by the weight of cement.

Based on the chosen optimum gauging of the complex modifying agent components the physical and mechanical properties of the modified self-compact concrete were established (Tables 2, 3).

The modified self-compact concrete has a grade class B50, high freeze-thaw resistance and water resistance under the R5 flow class.

Studying the structure formation of the cement stone of the modified SCC is a top scientific question.

The phase composition of cement stone hydrated newgrowths was determined by means of X-ray phase analysis and electron microscopy method.
Table 2. The properties of the concrete mix.

| Property                        | Parameter |
|---------------------------------|-----------|
| Density, kg/m³                  | 2470      |
| Flow class                      | R5        |
| Cone slump class                | P5        |
| Concrete desintegration:        |           |
| Segregation, %                  | 2.7       |
| Water gain, %                   | 0.45      |
| Temperature, °C                 | 25        |
| Storability of properties, h    | 2         |

Table 3. The properties of the modified self-compacting concrete.

| Property                                         | Parameter     |
|--------------------------------------------------|---------------|
| Compression strength at 3 days, MPa              | 42.5          |
| Compression strength at 7 days, MPa              | 56.9          |
| Compression strength at 28 days, MPa             | 64.62         |
| Tensile strength under bending at 28 days, MPa   | 8.98          |
| Critical stress intensity factor                 | 1.864         |
| Concrete modulus of elasticity, MPa              | 39.4·10³      |
| Waterproofing class                             | W16           |
| Freeze-thaw resistance class                     | F600          |
| Concrete shrinkage, mm/m                         | 0.2           |

There is an intricate structure of cement in Figure 5-8.

Figure 5. Electron microphotographs of samples of cement stone: spall of the sample with no admixture, magnification 100³

Figure 6. Electron microphotographs of samples of cement stone: spall of the sample with complex modifying agent, magnification 100³

There are needle crystals of ettringite in jellous mass of hydrated newgrowths in composition with complex admixture, which fill the free space. The hydrated newgrowths of ettringite are produced in free volume. There is the pore bridging by hydrated calcium sulfoaluminate at electron microphotographs of the samples of cement stone with adding the modifying agent. Furthermore,
these hydrated newgrowths have lower dispersive capacity, than the formations without admixture. The increasing of hydrated calcium sulfoaluminate concentration in pore spaces, specific surface area of hydrated phases lead to the hardening of material both in the general structure of cement stone and in structure with regions of imperfections.

The compacting and hardening of the structure during the initial stage of hydration is due to the fact that hydrated calcium sulfoaluminate is crystallized with volume increase in pore spaces of cement stone, which you can see in Figure 8. Additionally, there are pore spaces in composition with complex modifying agent that are smaller than the pore spaces in samples in Figure 5,6.

![Figure 7. Electron microphotographs of samples of cement stone: spall of the sample with no admixture, magnification 2000x.](image1)

![Figure 8. Electron microphotographs of samples of cement stone: spall of the sample with complex modifying agent, magnification 2000x.](image2)

The degree of the complex modifying agent influence on the product composition of cement hydration was analyzed with the use of X-ray phase analysis. The diffractograms of the samples are shown in Figure 9.

As you can see at the Figure 9, the samples have the diffraction reflections of unhydrated minerals of Portland clinker, videlicet C₃S – alite (3.3480; Å), C₂S – belite (4.8660; Å), C₄AF – celite (7.3202; Å), C₃A – tricalcium aluminate (2.7090; Å) and hydrated newgrowths Ca(OH)₂ – calcium hydrate (4.9247;2.6309;1.9287;1.7971 Å), calcium hydrates CSH (2.7517 Å), hydrosulfoaluminate (9.7544; 5.6201; 3.8766; 2.4968 Å). Interplanar spaces are listed within the brackets.

It is seen from phase composition analysis of cement stone that the number of low-basic hydrosilicates in the sample with complex modifying agent is 20% greater than the number of low-basic hydrosilicates in composition with no admixture. There is also the decreasing of the number of cement clinker original constituent: for unhydrated alite – 35% smaller, for belite – 10% smaller. The number of Portlandite is significantly lowered in composition 2 (40%). The increasing of the number of hydrated calcium silicates in composition 2 helps the hardening of material, which is confirmed by increased strength in the samples and by the electron microscopy data.

By reference the undertaken studies, namely, X-ray phase analysis and electron microscopy, it may be concluded that the reduced content of calcium hydroxide in samples with a complex modifying agent is a result of the calcium hydroxide adsorption on the fine particles and of the reaction of interaction with metakaolin, that also leads to the content reduction of calcium hydroxide in cement stone.

Thus, we found out the mechanism of the complex modifying agent influence on the structure formation and phase composition of the cement stone.
Figure 9. The curves of the X-ray phase analysis of cement stone: 1 – the sample, 2 – the sample with complex modifying agent.

4. Conclusions
1. The composition of the self-compacting concrete for flat roofs was made in this study. The main physical and mechanical properties of the SCC were measured from the perspective of the substantial increase of concrete strength and longevity.
2. The increase of the concrete longevity is a result of formation the fine-crystalline and finely-divided microstructure of cement stone, the ettringite in bugholes and capillaries of cement stone, and also the low-basic hydrated calcium silicate, which was shown by means of X-ray phase analysis and electron microscopy.
3. The modified SCC for the flat roofs sealing of the buildings has high performance characteristics: grade class is B55, freeze-thaw resistance class is F600, waterproofing class is W16, crack resistance of concrete that is shown by critical stress intensity factor eq 1.864.

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Reference
[1] Denisova Ju V, Tarasenko V N and Lesovik R V 2016 The diffusion membrane in modern construction Vestnik Belgorodskogo gosudarstvennogo tehnologicheskogo universiteta im.
[2] Fedorevskaja A A 2015 Modern materials for roofing *Izvestiya of Rostov State Building University* vol 2 20 pp 57–63

[3] *Guidelines for Design and Construction of roofs made of polymeric membranes* Retrieved from http://www.tn.ru/klarnetCMSlocal/modules/documents/get_with_original_name.php?obj_id =11742

[4] Domnin V V and Domnin K V 2011 *Concrete without rolling roof* (St.-Petersburg: StroiPROFI") 1(87) p 20

[5] 2009 *A technical report on the results of a survey of the roof of the building located at: Novosibirsk, Kropotkin st., 128/3, “InvestStroyTrans”* Retrieved from http://toist.ru/_ld/0/2_Gmb.pdf

[6] Izotov V S, Ibragimov R A and Bogdanov R R 2014 *No roll monolithic roof* (RU Patent 137685)

[7] Izotov V S, Ibragimov R A, Bogdanov R R and Ibneev B T 2014 *No roll monolithic roof* (RU Patent 141336)

[8] Bolotskih O N 2008 Self-compacting concrete and its diagnosis *Technologies of concrete* 10 pp 28–31

[9] Okamura H and Ouchi M 2003 *Self-Compacting Concrete Advanced Concrete Technology* 1 pp 5–15

[10] 2005 *The European guidelines for self-compacting concrete: specification, production and use* (UK) p 21

[11] Kirsanova A A and Kramar L Ya 2013 *Organic-based modifiers metakaolin for cement concrete* (Moscow: Stroitel'nye materialy) 11 pp 54–56

[12] Sheinfel'd A V 2014 Organic-modifiers as a factor that increases the durability of reinforced concrete structures *Concrete and reinforced concrete* 3 pp 16–21

[13] Kalashnikov V I, Khvastunov A V and Khvastunov V L 2011 Physical and mechanical and hygrometric properties of powder-activated high crush concrete and fiber-reinforced concrete with a low specific consumption per unit of cement strength *Scientific and Technical Herald of the Volga Region* 5 pp 161–164

[14] Izotov V S, Ibragimov R A and Bogdanov R R 2013 *Studies of the influence of super– and giper plasticizers on the basic properties of cement paste* (Kazan: Izvestiya KazGASU) 2(24) pp 221–225

[15] Izotov V S, Ibragimov R A and Bogdanov R R 2013 *Studies of the influence of domestic water-repelling additions on the basic properties of cement paste and mortar* (Kazan: Izvestiya KazGASU) 4(26) pp 207–210