KAUNAS UNIVERSITY OF TECHNOLOGY

ALBERTAS KLOVAS

THE INFLUENCE OF CONCRETE MIXTURE'S RHEOLOGICAL PROPERTIES ON FORMED MONOLITHIC CONCRETE SURFACE QUALITY AND ITS EVALUATION

Summary of Doctoral Dissertation

Technological Sciences, Civil Engineering (02T)

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

ALBERTAS KLOVAS

REOLOGINIŲ BETONO MIŠINIO SAVYBIŲ ĮTAKA MONOLITINIŲ KONSTRUKCIJŲ PAVIRŠIAUS KOKYBEI BEI JOS VERTINIMAS

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INTRODUCTION

Recently, more and more buildings in Lithuania and other countries have been built of monolithic concrete without additional surface decoration. Surfaces of monolithic concrete must be in a very good condition: smooth and without pores, should have an aesthetical appearance and feature various compositions: wood or masonry, etc. The issue of concreting without additional decoration exists not only in Lithuania but in other countries as well.

The most common problems are as follows: the unacceptable constitution of the concrete compound; the unacceptable concreting technology (i.e. concreting in forms); the unacceptable concrete compaction and others.

This issue is very relevant because many companies are producing and selling various compounds designed for concrete surface maintenance.

In addition, at the moment, there are no widely accepted rules in European standards to regulate the quality of concrete surfaces. Currently in Lithuania, the old GOST 13015.0-83 standard is still being used so that to evaluate the quality of a concrete surface.

In order to achieve the success in concreting without the additional decoration, it is necessary to obtain suitable concrete mixture compositions as well as to achieve the corresponding rheological and technological properties.

It is also necessary to develop research methods which would ensure the desired concrete surface quality. Also, the quality parameters of a concrete surface should be developed and investigated. A subjective method for the concrete surface quality evaluation should be adopted.

The aim

The development of constructional concrete with a controlled high surface quality.

The main tasks

1. To establish the dependence between the amount of fine particles, the fineness versus the coarseness of the aggregate and the rheological properties of the mixture. To improve the current equation to establish the mixture's plastic viscosity by adding a coefficient which would describe a variation in plastic viscosity when various admixtures are used.
2. To establish the dependence of the mixture's rheological properties on the quality of the formed concrete surface when using the upgraded methodology.
3. To modify the composition of the conventional concrete mixture according to the obtained rheological and the newly formed concrete surface properties.
4. To classify concrete surfaces according to their influence on the mixture's rheological properties on the distribution of concrete surface blemishes.

Novelty of a research

1. An equation describing a concrete mixture's plastic viscosity was improved by adding the coefficient of plastic viscosity variation.
2. It was established that the amount of fine particles exerted the most prominent influence on the mixture's rheological properties and on the quality of the formed concrete surface.
3. The effectiveness of air entraining admixture on the improvement of the formed concrete surface quality was established.

Methods of the research

Technological properties of concrete mixtures were established according to the standardized requirements; rheological properties of conventional concrete mixtures were calculated based on equations obtained in the course of literature review; the plastic viscosity of cement slurries was obtained with viscometer *Rheotest RN4*; an assessment of the concrete surface quality was conducted by using image analysis method *BetonGUI 2.0*; concrete surfaces were classified according to their quality by adhering to GOST 13015.0-83 and CIB report No. 24 requirements.

Practical relevance

The influence of various admixtures on a mixture's plastic viscosity can be obtained by utilizing the coefficient of plastic viscosity variation. Main factors for this evaluation of the concrete surface quality were obtained by utilizing the upgraded image analysis methodology. The number of blemishes, their size and area distribution are the main factors when considering the quality of a concrete surface. It is possible to foresee a variation in concrete rheological properties by selecting compound elements of concrete mixtures. It would be possible to evaluate and classify concrete surfaces according to their quality by validating the findings of this research in "TK 19 Concrete and reinforced concrete".

Statements presented for defense

1. The improved viscosity equation allows to evaluate the influence of concrete admixtures on plastic viscosity more precisely.
2. The n number and area of surface blemishes decreases when bigger amounts of fine particles and coarse aggregate are used. The employment of plasticizing admixture enables to obtain higher quality concrete surfaces and to reduce the yield stress and plastic viscosity of a concrete mixture.
3. The employment of air entraining admixtures reduces the yield stress and the plastic viscosity of the conventional concrete mixture. The air entraining admixture does not allow the formation of bigger surface air pores and divides them into a few smaller ones thus improving the quality of the formed concrete surface.

Scientific approbation of the dissertation

2 scientific articles based on the dissertation results were published in journals containing the citation index and referred in the database of *ISI Web of Science*. In addition, 5 articles were published in peer-reviewed international journals. Dissertation results were publicly presented in 9 scientific conferences in Lithuania and abroad.

1. LITERATURE REVIEW

Evaluation of the formed concrete surface quality may be conducted in several different ways. Danish Technical University suggested one of the methods (Bartos et al. 2002). Their assessment method was applied for self-compacting concrete mixtures (SSC) thus evaluating the influence of rheological properties on the surface quality. It must be taken into the consideration that this method provides only approximate evaluation opportunities. It is very important to obtain the perfectly designed concrete mixture composition in order to produce higher quality surfaces. There are a few fundamental specific limits of rheological properties providing different influence on the mixture's technological properties. Limit 1 (values of yield stress and plastic viscosity: 64 – 256 Pa; 8-32 Pa·s) – low risk of segregation; free surfaces can be controlled; sloping surfaces are possible; rough casting joints as well as troweling are possible. Limit 2 (values of yield stress and plastic viscosity: 64 – 256 Pa; 100 – 256 Pa·s) – risk of blowholes. Limit 3 (values of yield stress and plastic viscosity: 32 – 64 Pa; 100 – 256 Pa·s) – cohesive, sticky mixtures; bleeding is not common; risk of plastic shrinkage. Limit 4 (values of yield stress and plastic viscosity: 8 – 30 Pa; 50 – 100 Pa·s) – risk of segregation; free surfaces are difficult to control; "foam" concrete is possible; rough casting joints are difficult to obtain. Limit 5 – nice surfaces (values of yield stress and plastic viscosity: 8 – 30 Pa; 8 – 40 Pa·s); Area 6 (values of yield stress and plastic viscosity: 30 – 64 Pa; 8 – 40 Pa·s) – easy to work with; bleeding can occur. Systematic analysis of scholarly literature revealed that the topic of the impact of rheological properties on the surface quality had been scarcely researched; moreover, previous researches had been carried out on self-compacting concrete mixtures. No information had been found regarding conventional concrete mixtures; therefore, the top priority was to investigate the influence of rheological properties of conventional concrete mixtures on the quality of the formed concrete surface. Rheological properties of the conventional concrete mixture had been calculated analytically (Skripkiūnas 2007) by utilizing equations (1) and (2) presented below.

Yield stress was obtained by Equation 1:

$$\tau_0 = \frac{0.00815 \cdot \rho_m}{\left(\sqrt{\frac{0.498}{30 - SL} - 0.001724} - 0.024\right)^2}; \qquad (1)$$

here: τ_0 – yield stress established by mixture slump, kPa; ρ_m – density of the concrete mixture, g/cm^3; SL – slump of the concrete mixture, cm.

The plastic viscosity of the concrete mixture was calculated by Equation 2:

$$\eta_b = \eta_v \cdot \exp\left(\frac{a_c \cdot \rho_v}{\rho_v + \frac{V}{C} \cdot \rho_c - b_c \cdot \rho_v} + \frac{a_{sm}\left(1 - \varphi_{st} - \varphi_o - \frac{V}{\rho_v} - \frac{C}{\rho_c}\right)}{1 - \varphi_{st} - b_{sm}\left(1 - \varphi_{st} - \varphi_o - \frac{V}{\rho_v} - \frac{C}{\rho_c}\right)} + \frac{a_{st} \cdot \varphi_{st}}{1 - b_{st} \cdot \varphi_{st}} \right) \quad (2)$$

here: η_v – the dynamic viscosity of water in 20°C, Pa·s; φ_o – air quantity in the concrete mixture; V, C – amounts of water and cement (1 m³); ρ_v, ρ_c – densities of water and cement, kg/m³; φ_{sm}, φ_{st} – volume ratio of the fine aggregate in the slurry part and the coarse aggregate in the concrete mixture; a_c, a_{sm}, a_{st} – coefficients defining the form of particles: cement, fine and coarse aggregate (a_c = 2.6; a_{sm} = 2.5; a_{st} = 2.6); b_c, b_{sm}, b_{st} – coefficients representing the placement density of particles: cement, fine and coarse aggregate accordingly in the slurry and concrete mixture;

Equation (2) was modified with a coefficient describing the influence of various admixtures on the plastic viscosity of concrete mixture (3).

$$\eta_b = \eta_v \cdot \exp\left(\frac{a_c \cdot \rho_v}{\rho_v + \frac{V}{C} \cdot \rho_c - b_c \cdot \rho_v} + \frac{a_{sm}\left(1 - \varphi_{st} - \varphi_o - \frac{V}{\rho_v} - \frac{C}{\rho_c}\right)}{1 - \varphi_{st} - b_{sm}\left(1 - \varphi_{st} - \varphi_o - \frac{V}{\rho_v} - \frac{C}{\rho_c}\right)} + \frac{a_{st} \cdot \varphi_{st}}{1 - b_{st} \cdot \varphi_{st}} \right) \cdot K_{calc.} \quad (3)$$

here: $K_{calc.}$ – coefficient describing the change in the mixture's plastic viscosity when using various admixtures.

Technological properties of concrete mixtures adhered to Lithuanian standards: the slump test to LST EN 12350-2, the flow table test to LST EN 12350-5; the mixture density to LST EN 12350-6, the entrained air content to LST EN 12350-7.

Coefficient K_{cal} was established as a ratio between different viscosity values of cement slurries obtained without utilizing and by utilizing certain admixtures. Table 1 shows K_{calc} values.

Table 1. Coefficients describing the change in slurry viscosity when adding various types and amounts of admixtures

Num.	Amount., %	Plastic viscosity of cement slurry, Pa·s	Coefficient, $K_{calc.}$
Superplasticizer *Glenium SKY 628* only			
1	0	0.506	-
2	0.6	0.0930	0.184
3	0.8	0.0928	0.183
4	1.0	0.0430	0.085
5	1.2	0.039	0.077
6	1.4	0.039	0.077
7	1.6	0.043	0.085
Superplasticizer *Glenium SKY 628* (1.4 %) and air voids removing admixture *Rheomix 880*			
1	0	0.039	0.077
2	0.05	0.043	0.085
3	0.10	0.036	0.071
4	0.15	0.043	0.085
5	0.20	0.043	0.085
6	0.25	0.043	0.085
7	0.30	0.032	0.063
Superplasticizer “Glenium SKY 628” (1.4 %) and viscosity modifying admixture “Rheomatrix 100”			
1	0	0.039	0.077
2	0.1	0.032	0.063
3	0.3	0.032	0.063
4	0.5	0.032	0.063
5	0.7	0.032	0.063
6	0.9	0.034	0.067
7	1.1	0.046	0.091
Superplasticizer *Glenium SKY 628* (1.4 %) and air entraining admixture *Micro AIR G LP*			
1	0	0.039	0.077
2	0.05	0.029	0.057
3	0.10	0.029	0.057
4	0.15	0.029	0.057
5	0.20	0.029	0.057
6	0.25	0.03	0.059
7	0.30	0.032	0.063

1.1. Main methods used for quality evaluation of formed concrete surfaces

CIB (Concrete Industry Board) prepared a document (studies et al. 1974) according to which the quality of the formed concrete surface can be evaluated. Surface quality evaluation is based on the visual control scale which groups surfaces into 7 categories (Lemaire et al. 2005) (Fig. 1).

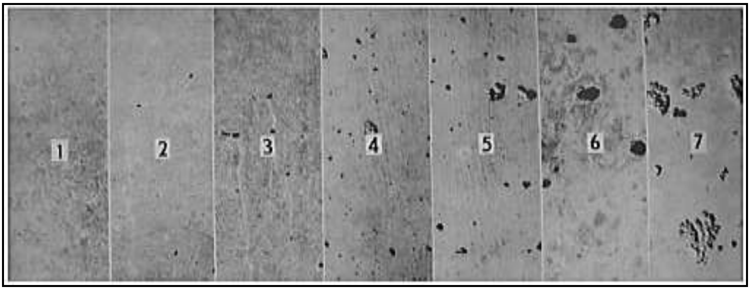


Fig. 1. Visual control scale used for the assessment of the concrete surface quality (CIB Report No. 24 1973)

CIB document (Commission W 29) divides concrete surfaces according to their quality into 4 main categories:

- Special concrete – the highest standards and requirements for concrete surfaces.
- High quality concrete – relatively high requirements for concrete surface quality but considerably lower compared to special concrete.
- Conventional concrete – surface quality is not the most important factor.
- Rough concrete – no requirements for concrete surfaces.

Assessment of the concrete surface quality is conducted as follows: two different cards from the control scale are placed on the tested object. The difference between the two numbers produces the identification of the concrete surface quality (Table 2). This method can be successfully applied if pores are distributed all over the tested surface.

Table 2. Assessment of the concrete surface quality according to CIB document.

Defect of concrete surface	Categories of concrete surfaces			
	Special	High quality	Conventional	Rough
Widely distributed concrete surface pores. Maximal possible difference between card numbers for the same tested area	2-4	4-6	6>	-

Another concrete surface evaluation method is the improved CIB methodology (Commission W 29) (Lemaire, Escadeillas and Ringot, 2005). This method is based on image analysis. Each tested surface must be pictured from as close as possible in order to be able to evaluate defects as small as 1 mm^2. Scientists introduced the following algorithm:

- The “Median” filter is used in order to minimize the influence of some very small particles such as dust.
- Pores containing enormous sizes are removed.

- The quantity and size of surface air pores are obtained.

The open software code program *ImageJ* may be used in order to conduct the previously outlined tasks. This program evaluates the ratio of a specific element. The assessment procedure of the concrete surface quality is presented in Fig. 2.

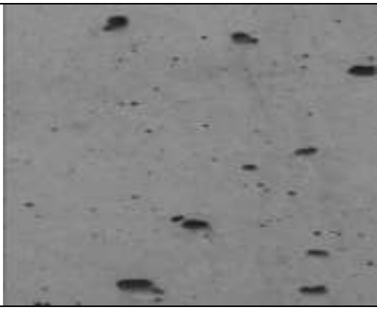
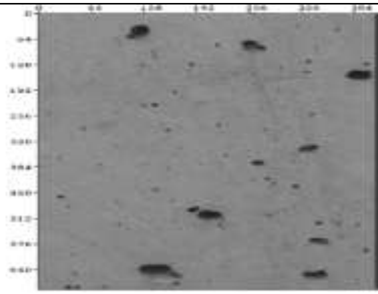
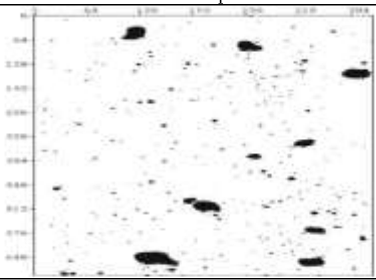
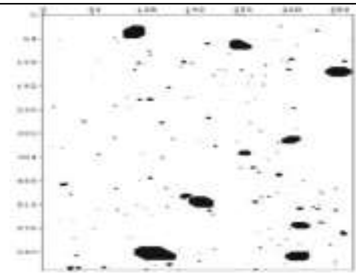
	
1. A concrete specimen	2. The ratio of the concrete surface is set
	
3. Defects are emphasized	4. Defects are marked and calculated

Fig. 2. The analysis of a concrete surface

As it can be seen in Fig. 3, scientists improved the method suggested by CIB. They established quantity and size of the surface pores. It is obvious that the highest number of pores is obtained within category of 4 and 5, namely, 5500 to 6500 units of blemishes. On the other hand, the 7th concrete surface features the largest area of surface blemishes. This suggests that the 7th concrete surface has the biggest surface blemishes although their number may decrease.

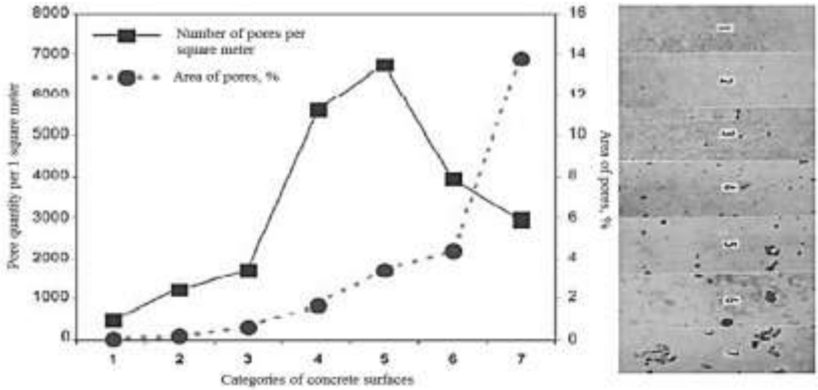


Fig. 3. The number and size of pores in respect to category (Lemaire, Escadeillas and Ringot, 2005)

The concrete surface quality may also be evaluated according to GOST 13015.0-83 standard. This methodology also divides concrete surfaces into categories from A1 to A7 where A1 defines the best surface quality while A7 – vice versa – stands for the lowest quality. Table 3 indicates the requirements of GOST 13015.0-83. It must be taken into the consideration that some pores (no more than 1 unit per 1 m^2) are allowed with bigger dimensions as follows:

- 2 mm – A2 category.
- 6 mm – A3 category.
- 15 mm – A4 category.

Table 3. Requirements for surface quality according to GOST 13015.0-83

Category of concrete surface	Pore's largest dimensions	Depth of local elevations or depressions	Depth of edge cracking	Common length of cracking in 1m edge
	Units, mm			
A1	Best surface quality		2	20
A2	1	1	5	50
A3	4	2	5	50
A4	10	1	5	50
A5	No requirements	3	10	100
A6	15	5	10	100
A7	20	No requirements	20	No requirements

Norwegian scientists from Norwegian University of Science and Technology (NTNU) and SINTEF offered to conduct an assessment of the concrete surface quality by evaluating the number and size of surface pores (Eide et al. 2011). Recently, the BIM method has been widely used and, together with 3D laser scanning technology, it provides the possibility to evaluate the surface quality of pre-cast concrete elements (Kim et al. 2015). However, there are some drawbacks of this method: concrete surfaces of pre-cast elements can only be evaluated, and, more importantly, the thickness of specimens cannot vary.

2. METHODOLOGY OF THE RESEARCH

2.1. Description of study

Compositions of concrete mixtures were chosen according to LST 1974:2012 requirements. Dry aggregates were used for the preparation of concrete mixtures. Admixtures were added in a concrete mixture together with water except for the viscosity-modifying admixture. The amount of admixtures was calculated in percentage in respect to the cement quantity. 42 different concrete compositions were designed. The aim was to optimize the rheological properties of the mixture (i.e., its yield stress and plastic viscosity) in order to obtain the best possible concrete surface quality. Striving to define the influence of different mixture components, all the experiment was divided into 7 main stages as can be seen in Fig. 4.

Computer software *BetongGUY 2.0* was chosen for the evaluation of the concrete surface quality. During the author's PhD internship (March 01 – June 01, 2013) at Norwegian University of Science and Technology (NTNU), together with "SINTEF", this program was tested and permission for PhD researches was received. The program was being tested and evaluated as a part of the international research project *COIN FA 2.1 Highly flowable concrete with controlled surface*. This software is still being developed in "SINTEF" laboratories.

Below is the description of the equipment used for the image taking procedure:

- Camera: "Nikon D3200";
- Lens: „Nikon DX AF-S NIKKOR 18-55";
- Flashlight: "Quantuum";
- Light diffuser: "PhotoFlex LiteDome Q39 soft box medium";
- White color calibration sheet: "Lastolite".

What concerns the lens sensitivity (ISO), the actual sensitivity of the lens is changed by adjusting the ISO value. A lower ISO number means that less light goes through the lens; therefore, the camera is less sensitive for light. It is recommended using high ISO values where the surrounding is dark and the flash utilization is not possible (Peterson 2008). The ISO value was minimal and set to 100 value during the research.

Reference concrete mixture composition obtained from UAB "Kauno gelžbetonis". Two differently fractioned (0/1 and 0/4 mm) types of sand were used as fine aggregate.

Stage I. Only the ratio between the fine aggregate (0/1 and 0/4 mm) was changed. The other components of the mixture were stable.

BA1-0, (0.11/0.37)	BA1-1, (0.16/0.32)	BA1-2, (0.21/0.27)	BA1-3, (0.26/0.22)	BA1-4, (0.31/0.17)	BA1-5, (0.36/0.12)

Stage II. Only the ratio between coarse (gravel, fraction 4/16 mm) and the total mixture aggregate were chnaged. The other components of the mixture were stable.

BA2-0, (1-1), 0.22	BA2-1, 0.32	BA2-2, 0.42	BA2-3, 0.52	BA2-4, 0.62	BA2-5, 0.72	BA2-6, 0.82

Stage III. The amount of cement in 1 m^3 of mixture was changed. The other amounts of the mixture components were stable

BA3-0, (2-0), 180	BA3-1, 230	BA3-2, 280	BA3-3, 330	BA3-4, 380	BA3-5, 430	BA3-6, 480

Stage IV. The amount of plasticizing admixture was changed. The other amounts of the mixture components were stable.

BA4-0, (3-4), 0.6	BA4-1, 0.8	BA4-2, 1.0	BA4-3, 1.2	BA4-4, 1.4	BA4-5, 1.6	BA4-6, 1.8

Stage V. An amount of air voids removing admixture had been changed. The other amounts of the mixture components were stable.

BA5-0, (4-4), 0	BA5-1, 0.05	BA5-2, 0.1	BA5-3, 0.15	BA5-4, 0.20	BA5-5, 0.25	BA5-6, 0.30

Stage VI. The amount of the viscosity modifying admixture was changed. The other amounts of the mixture components were stable.

BA6-0, (5-0), 0	BA6-1, 0.1	BA6-2, 0.3	BA6-3, 0.5	BA6-4, 0.7	BA6-5, 0.9	BA6-6, 1.1

Stage VII. The amount of the air entraining admixture was changed. The other amounts of the mixture components were stable.

BA7-0, (6-0), 0	BA7-1, 0.05	BA7-2, 0.10	BA7-3, 0.15	BA7-4, 0.20	BA7-5, 0.25	BA7-6, 0.30

Fig. 4. Main stages of the experiment

The main purpose of the flash light utilization is to maximally eliminate the varying illumination of the environment. Table 4 presents the parameters that were set and used for the further testing.

Table 4. Optimal properties of the photo taking equipment

Parameters of the image taking equipment			
Relative aperture, F	Shutter speed, s	ISO	Intensity of flash light, GN
8	1/160	100	15

Flash light was placed at approximately 45º against the tested surface at a distance of 0.5 – 0.6 m. Fig. 5 illustrates the positioning of the image taking equipment during the test.

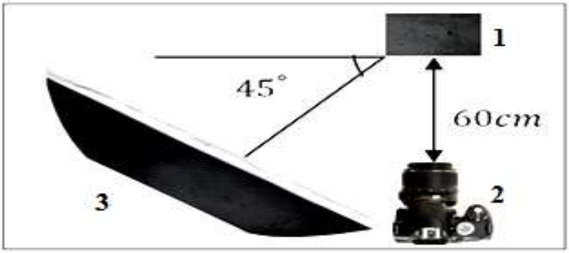


Fig. 5. Positioning of the image taking equipment: 1 – the researched specimen; 2 – the photo-camera; 3 – the flashlight box.

Fig. 6 indicates the assessment process of the concrete surface quality by using *BetongGUY 2.0*.

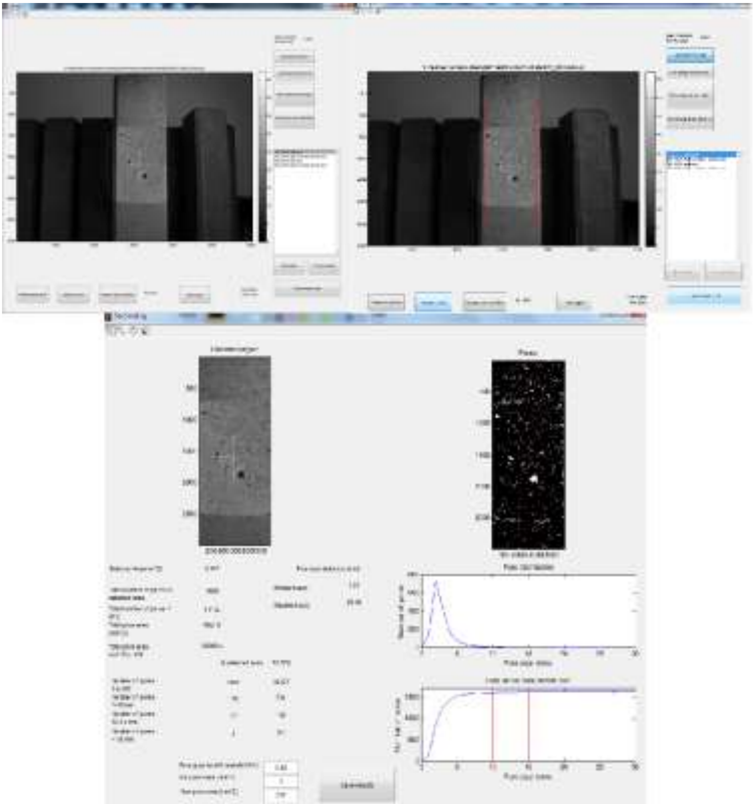


Fig. 6. An assessment process of images

It must be noted that only RAW format of images had been used for "BetongGUY 2.0". Ratio between real measurements and those in the images is one of the most important factors. It must be set carefully and precisely. The outcome results of a program is a number of surface pores and their areas.

3. RESULTS

This part of the research describes the influence of the rheological properties (yield stress and plastic viscosity) of the mixture on the surface quality of the concrete. The quality of concrete surfaces was evaluated by using the program *BetongGUY 2.0*. The influence of the different mixture components on the produced concrete surface quality was obtained. Fig. 7 shows the evaluation scale of concrete surfaces (da Silva et al. 2014).

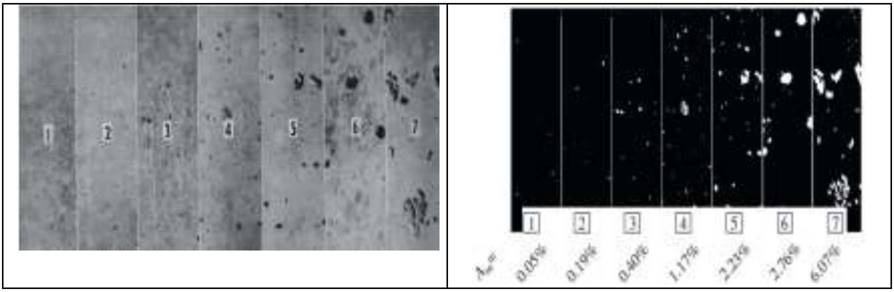


Fig. 7. The evaluation scale of concrete surfaces (da Silva, Lucena, Štemberk and Prudêncio Jr., 2014).

The outcome results of *BetongGUY 2.0* featured a number of surface pores and outlined their biggest dimensions. In order to classify the surfaces according to their quality, only the biggest pores were taken into the consideration (10 – 15 mm and >15 mm.). In addition, surface blemishes were treated as circles with the following radiuses: 5 mm for 10 to 15 mm and 7.5 mm for >15 mm. Concrete surfaces were classified according to the total area of pores per 1 m^2 according to CIB (Concrete Industry Board) scale (Fig. 7) and GOST 13015.0-83 requirements.

3.1. The influence of concrete mixture rheological properties obtained by changing the ratios between the amounts of fine aggregate on the quality of the formed concrete surface

The influence of the ratio between the fine aggregate on the formed concrete surface quality was established. 3 different ratios for fine aggregate were selected according to the previously established rheological properties: 0.297 (BA1-0: 132.85 Pa; 0.973 Pa·s) as the reference point with the lowest ratio; 0.500 (BA1-1: 181.00 Pa; 1.764 Pa·s) as the intermediate point; 1.824 (BA1-4, 226.00 Pa; 1.780 Pa·s) as the limit point with the biggest ratio.

The main parameters for quality evaluation were the number of air pores per 1 m^2 and their size. Air the pores were classified not only by their quantity but also by the biggest dimensions as well: 1 – 5 mm, 5 – 10 mm, 10 – 15 mm and bigger than 15 mm. The attention was focused on the bigger air pores: 10-15 mm and >15 mm. The bigger pores are more noticeable from the distance and therefore more important in terms of assessing the quality of the produced concrete surface.

Fig. 7 indicates the dependence between the mixture's yield stress and the area of surface blemishes when changing the amount of fine aggregate.

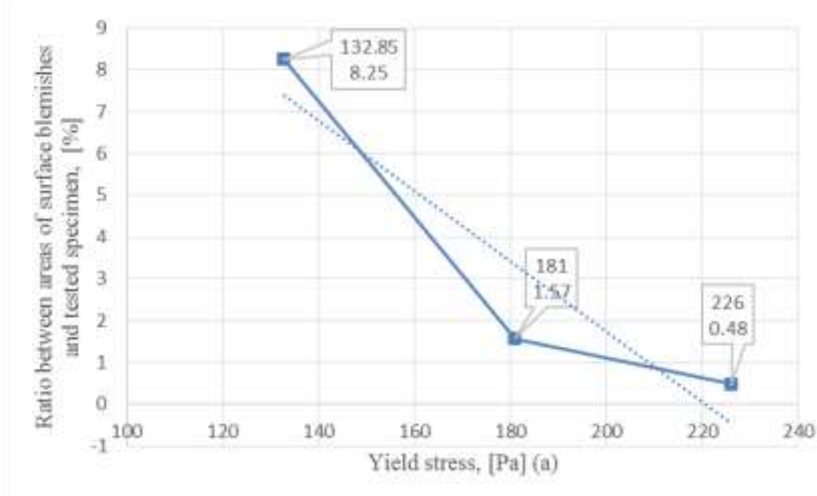


Fig. 8. The dependence between the mixture`s yield stress and the concrete surface quality

As it can be obtained from Fig. 8, the quantity of surface air pores per 1 m^2 significantly declines with an increase of 0/1 fr. sand. An increase of the fine aggregate 0/1 fr. resulted in the inclination of the yield stress.

Fig. 9 presents the dependence between the mixture's plastic viscosity and its surface quality.

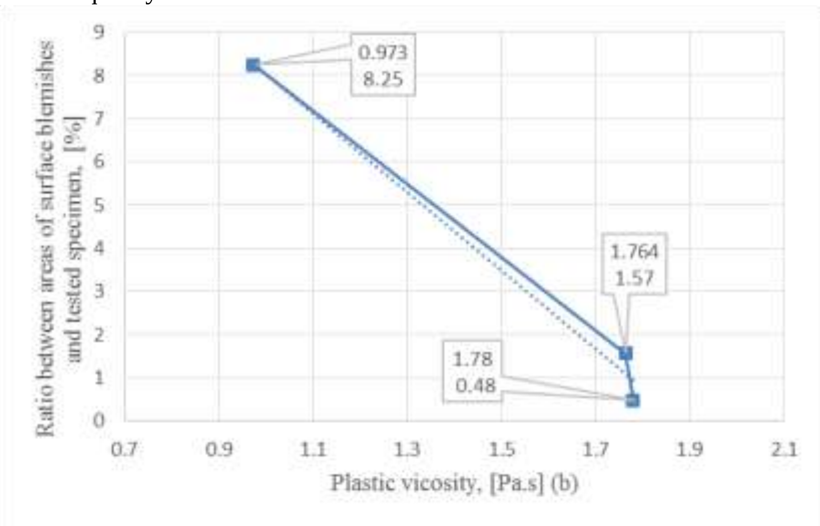


Fig. 9. The dependence between the mixture's plastic viscosity and the concrete surface quality

It must be noted that a number of bigger air pores reduced. Air pores 10 – 15 mm declined from 359 to 43 units and >15 mm diminished from 307 to 6 units per 1 m^2. Based on results, it can be stressed out that an increase of fine aggregate resulted in an inclination of mixture`s yield stress and plastic viscosity and also ended up with higher quality concrete surfaces.

3.2. An influence of concrete mixture rheological properties obtained by changing a ration between the amount of coarse and total aggregate on formed concrete surface quality

3 different ratios between amounts of coarse and total aggregate were taken into the consideration. Specimens: 0.32 (BA2-2: 1541 Pa; 8.473 Pa·s) – reference point with the lowest ratio; 0.52 (BA2-0: 132.00 Pa; 1.764 Pa·s) – an intermediate point with a medium ratio; 0.72 (BA2-5: 341 Pa; 6.375 Pa·s) – a limit point with the biggest ratio.

Fig. 9 presents a dependence between mixture`s yield stress and area of surface blemishes when changing an amount of coarse aggregate.

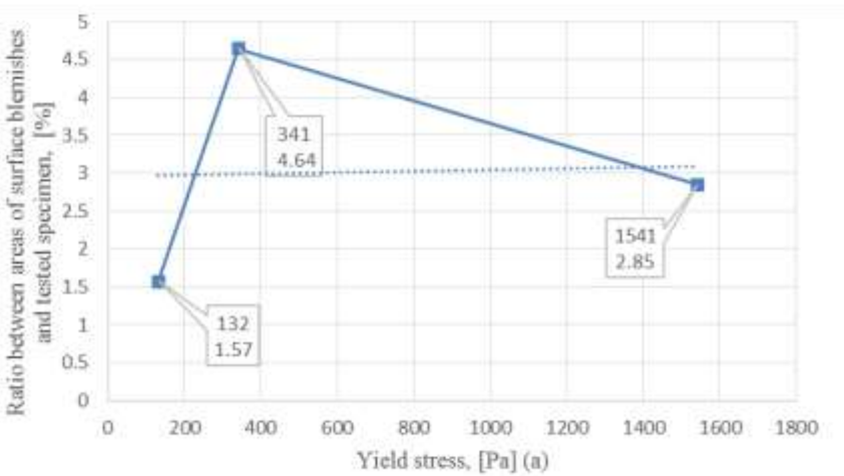


Fig. 9. A dependence between mixture`s yield stress and concrete surface quality

As presented in Fig. 9, an increase of yield stress from 132 Pa to 341 Pa and plastic viscosity from 1.764 Pa·s to 6.375 Pa·s (Fig. 10) significantly worsened concrete`s surface quality. It must be stressed out that segregation occurred to BA2-5 concrete mixture although it showed the best results. It occurred due to appearance of cement milk which filled in visible surface pores. Quantity of 10-15 mm surface blemishes decreased from 148 to 117 units and >15 mm declined from 96 to 37 units.

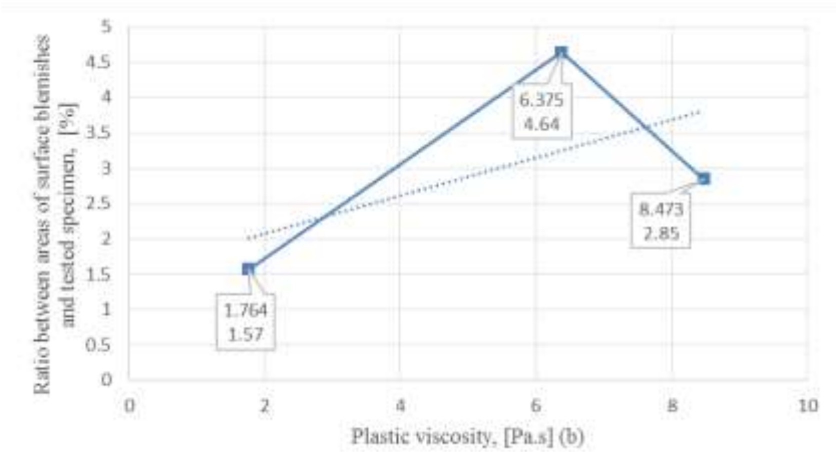


Fig. 10. A dependence between mixture`s plastic viscosity and surface quality

Looking from the perspective of aggregate ratio, a further increase from 0.52 to 0.72 resulted in a significantly higher number of surface blemishes: 10-15 mm increased from 117 to 200 units and bigger blemishes >15 mm from 37 to 174. It was obtained that within a ratio of 0.52 the highest surface quality was obtained. This might occurred due to an optimal packing degree of aggregates.

3.3. An influence of concrete mixture rheological properties obtained by changing amounts of fine particles on formed concrete surface quality

4 different concrete specimens obtained by different mixture compositions were tested. Amount of fine particles (cement together with sand up to 0.25 mm) was gradually increased: ~441 kg (BA3-2: 439 Pa; 4.29 Pa·s) – reference point with the lowest amount; ~520 kg (BA3-0: 180.54 Pa; 1.76 Pa·s) and ~560 kg (BA3-4: 184 Pa; 1.683 Pa·s) – intermediate points and ~600 kg (BA3-5: 180 Pa; 1.622 Pa·s) – limit point with the biggest amount.

Fig. 11 presents the dependence between the mixture’s yield stress and area of surface blemishes when changing the amount of fine particles.

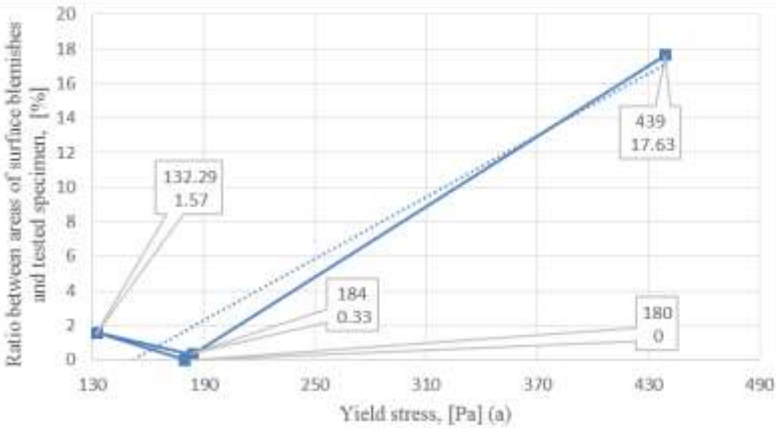


Fig. 11. The dependence between a mixture's yield stress and the concrete surface quality

The incline of fine particles resulted in the significant decline of the mixture's yield stress and plastic viscosity (Fig. 12).

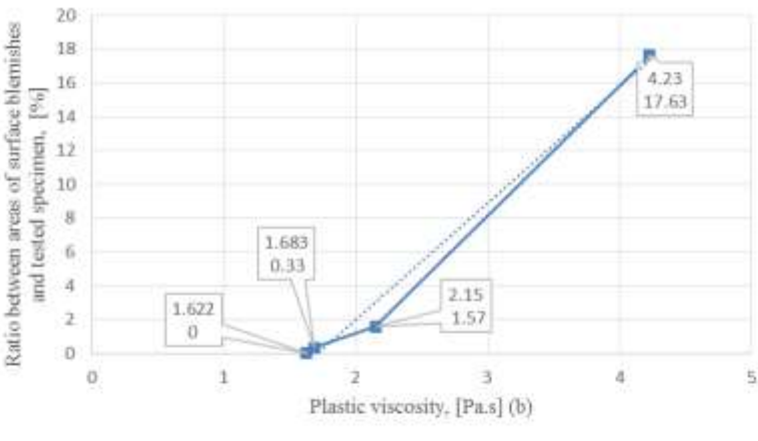


Fig. 12. The dependence between the mixture's plastic viscosity and the formed concrete surface quality

It was observed that the number of air pores sized 10-15 mm decreased from 830 units to 0 whereas bigger pores disappeared completely from 630 units to 0. The amount of fine particles was the most prominent factor which had influence on the concrete surface quality. It is obvious that the higher the amount of cement is, the higher surface quality is consequently obtained. However, a drawback develops that cement is the most expensive part of the compound and therefore the final price of the concrete mixture increases.

3.4. The influence of the rheological properties of the concrete mixture obtained by changing the amount of superplasticizer on the formed concrete surface quality

The quantity of superplasticizer is altered

In order to conduct a test of the superplasticizer's (SP) (based on polycarboxylic ether polymers) influence on the formed concrete surface quality, 4 concrete specimens formed of different mixtures were prepared. 4 different dosages of superplasticizer were selected: 0.8 % (BA4-2: 286 Pa; 1.493 Pa·s) – the reference point with the lowest amount; 1.2 % (BA4-0: 184 Pa; 1.683 Pa·s) and 1.4 % (BA4-4: 243 Pa; 1.9 Pa·s) – the intermediate points; 1.6 % (BA4-5: 182 Pa; 1.963 Pa·s) – the limit point with the biggest amount.

Fig. 13 presents the dependence between the mixture's yield stress and the area of surface blemishes when altering the amount of the superplasticizer.

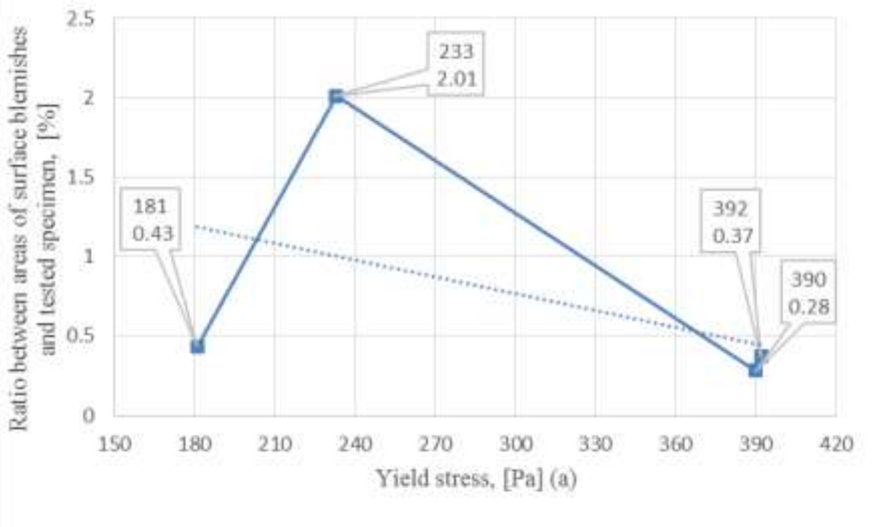


Fig. 13. The dependence between the mixture's yield stress and the formed concrete surface quality

As it can be seen in Fig. 13 and 14, the ratio of surface defects was not high, measuring at about ~0.3 % (yield stress 180 Pa; plastic viscosity 1.5 Pa·s). More surface pores were obtained when yield stress values increased to 230 Pa and the plastic viscosity rose to 1.9 Pa·s.

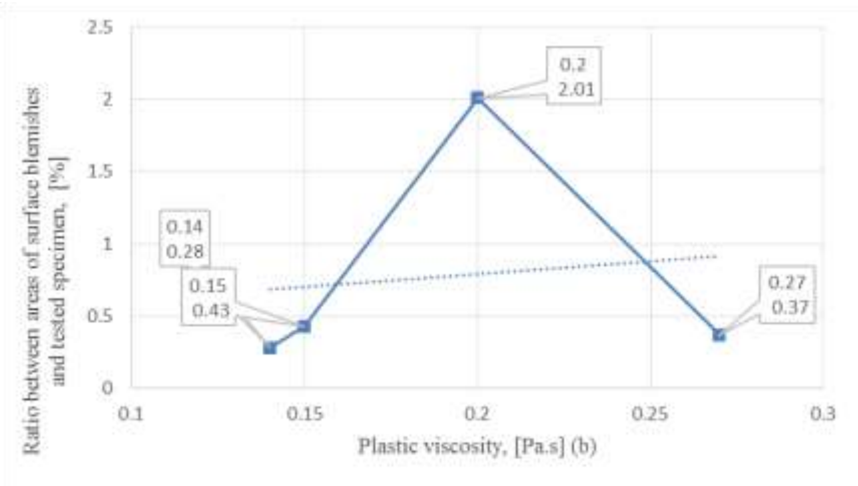


Fig. 14. The dependence between the mixture's plastic viscosity and the formed concrete surface quality

An increase of SP from 0.8 to 1.2 % showed a decrease in the number of surface pores: the size of 10-15 mm from 22 to 18 and the size exceeding >15 mm from 11 to 7. A further increase of SP from 1.2 to 1.4 % significantly increased the number of surface blemishes: sized 10-15 mm – from 18 to 156 units while exceeding >15 mm – from 7 to 44 units. It is also obvious that an increase of SP up to 1.6 % resulted in visually good looking surfaces. This was caused by the mixture's segregation and, as previously mentioned, the cement milk filled in surface gaps. Unfortunately segregated mixtures cannot be utilized.

To sum up, the quantity of SP exerted differing influence on the mixture's behavior and its properties; therefore the surface quality was affected differently as well. The optimal amount of SP was established to be 1.2 % of cement amount.

The quantity of air voids removing admixture is changed

In order to conduct a test of air voids removing (AVR) admixture (based on propoxylated and ethoxylated fatty acids) and the influence on the formed concrete surface quality, 3 concrete specimens formed of different mixtures were prepared. 3 different dosages of AVR were chosen: 0 % (BA5-0: 234 Pa; 1.9 Pa·s) as the reference point with the lowest amount; 0.15 % (BA5-3: 232 Pa; 1.942 Pa·s) as the intermediate point with the medium amount; 0.30 % (BA5-6: 232 Pa; 1.953 Pa·s) as the limit point with the biggest amount.

Fig. 15 presents the dependence between the mixture's yield stress while Fig. 16 shows the link between the mixture's plastic viscosity on the area of surface air pores while changing the amount of AVR.

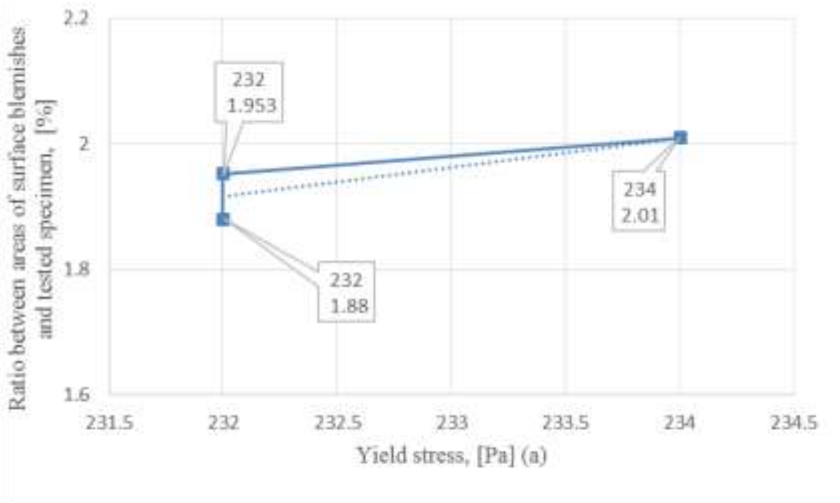


Fig. 15. The relationship between the mixture's yield stress and area of surface blemishes while changing the amount of air voids removing admixture

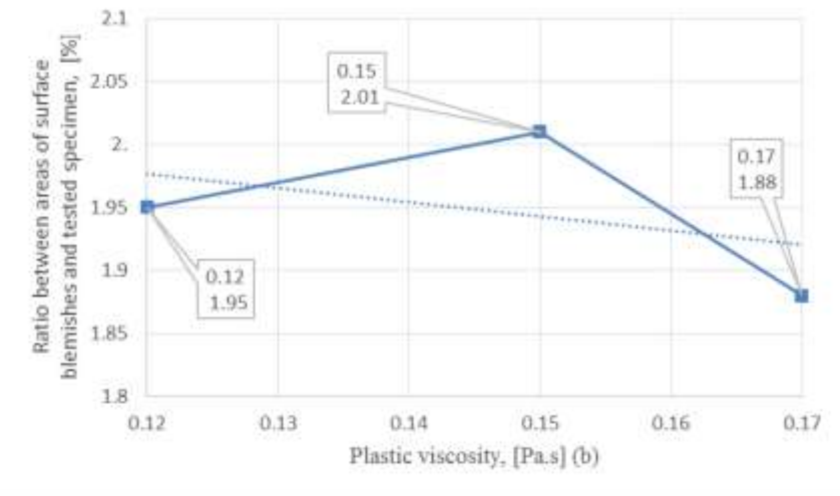


Fig. 16. A link between the mixture's plastic viscosity and the area of surface blemishes while changing the amount of air voids removing admixture

The influence of air voids removing admixture on the number of surface pores was almost unnoticeable; therefore, it was not taken into the account for the further research and conclusions.

The quantity of viscosity modifying admixture is changed

In order to conduct a test of the viscosity modifying admixture (VMA) (based on synthetic copolymers) influence on the formed concrete surface quality, 3 concrete specimens formed of different mixtures were prepared. 3 different dosages of VMA were chosen: 0 % (BA6-3: 234 Pa; 1.9 Pa·s) as the reference point with the lowest amount; 0.5 % (BA6-3: 285 Pa; 0.47 Pa·s) as the intermediate point with the medium amount; 1.1 % (BA6-6: 335 Pa; 1.759 Pa·s) as the limit point with the biggest amount.

Fig. 17 presents the dependence between the mixture's yield stress whereas Fig. 18 shows the link between the mixture's plastic viscosity on an area of surface air pores while changing an amount of VMA.

The results showed that the number of surface defects decreased with an inclination of VMA from 0 to 1.1 % of the cement amount. On the other hand, it did not show any noticeable influence regarding the mixture's yield stress. To conclude, 10-15 mm air pores reduced from 157 to 14 units while the bigger pores sized >15 mm declined from 44 to 1 unit per $1m^2$.

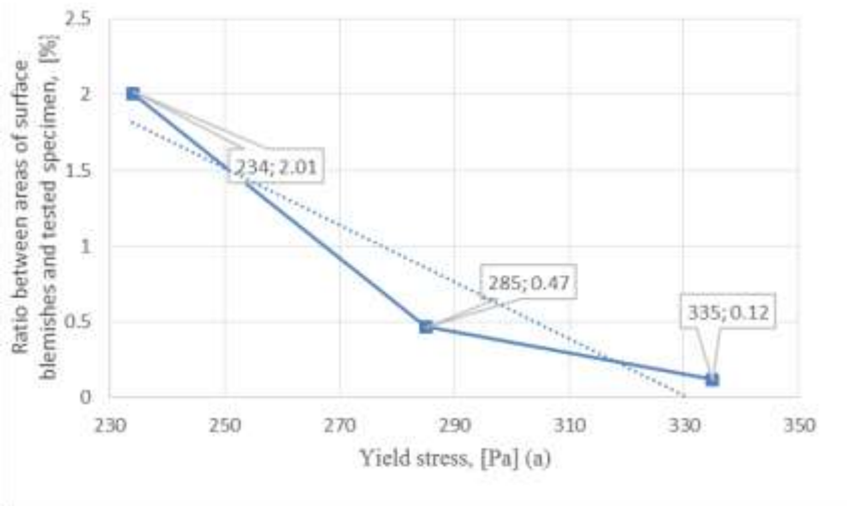


Fig. 17. A dependence between mixture`s yield stress and area of surface blemishes while changing the amount of viscosity modifying admixture

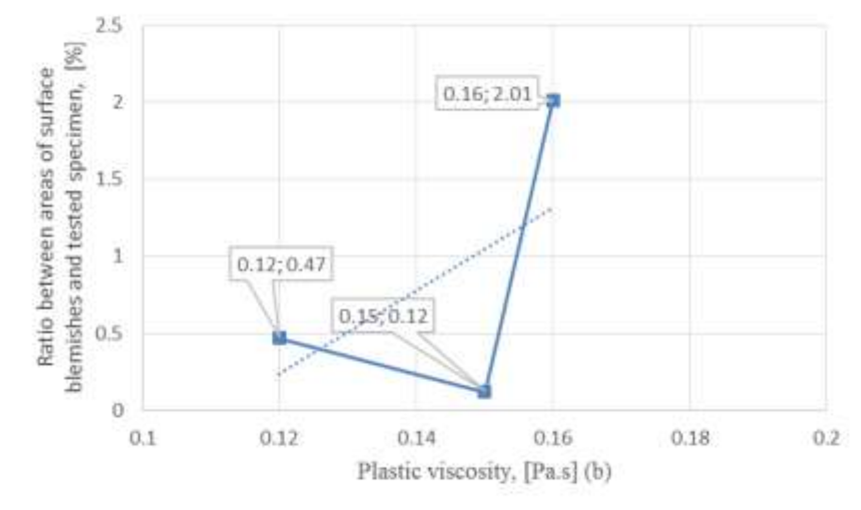


Fig. 18. A link between the mixture`s plastic viscosity and the area of surface air pores while changing the amount of the viscosity modifying admixture

It is obvious that VMA exerts positive influence on the concrete surface quality. Viscosity modifying admixture contains excess water inside the mixture and therefore water cannot be trapped on the surface of formworks. It helps to achieve better-looking concrete surfaces.

The amount of air entraining admixture is changed

In order to conduct a test of the air entraining admixture (AEA) based on surfactants and its influence on the formed concrete surface quality, 3 concrete specimens formed of different mixtures were prepared. 3 different dosages of AEA were chosen: 0 % (BA7-0: 234 Pa; 1.9 Pa·s) as the reference point with the lowest amount; 0.15 % (BA7-3: 183 Pa; 1.383 Pa·s) as the intermediate point with medium amount; 0.30 % (BA7-6: 182 Pa; 1.63 Pa·s) as the limit point with the biggest amount.

Fig. 19 presents the dependence between the mixture’s yield stress while Fig. 20 shows a link between the mixture’s plastic viscosity and the area of surface air pores while changing the amount of AEA.

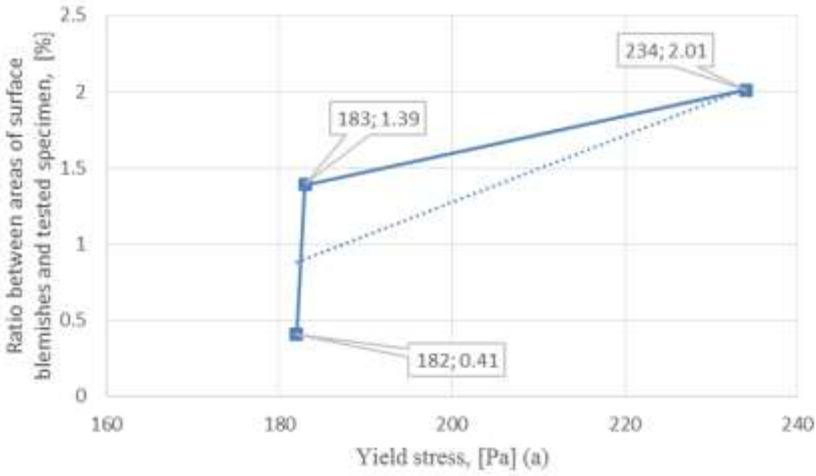


Fig. 19. The link between the mixture's yield stress and the area of surface air pores while changing an amount of the air entraining admixture

An increase of AEA from 0 to 0.15 % did not show any significant influence on the number of defects; however, it decreased the mixture`s yield stress from 234 Pa to 183 Pa. A further increase of AEA reduced the surface's defects; however, it did not influence the yield stress. On the other hand, the biggest change in the plastic viscosity was observed with 0.30 % of AEA (Fig. 20).

This research revealed that the utilization of air entraining admixture has a positive influence on the formed concrete surface quality. It must be taken into consideration that there are few popular well-grounded opinions about the AEA utilization. Some scientists believe that there is a more prominent possibility to obtain worsened concrete surfaces when utilizing AEA due to aggregate segregation (Contractors and Institute 2008).

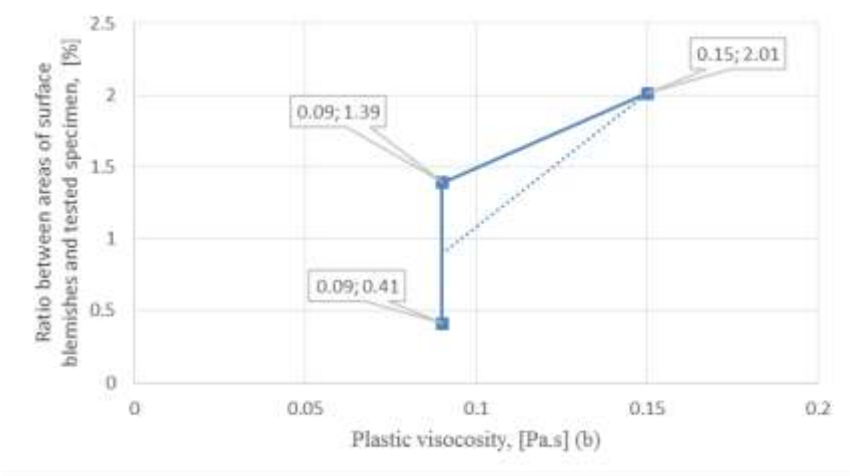


Fig. 20. The link between the mixture's plastic viscosity and the area of surface air pores while changing the amount of air entraining admixture

On the other hand, other scientists insistingly claim that the utilization of the air entraining admixture (Samuelsson 1970) usually improves the aesthetics of a concrete surface. This improvement might be caused by the tiny air pores that are entrained as pores likely act as a lubricant for the bigger ones to escape. The results obtained in this research confirmed that AEA might actually improve the quality of the formed concrete surfaces. Fig. 21 presents a scale of concrete surface quality evaluation based on the conducted research.

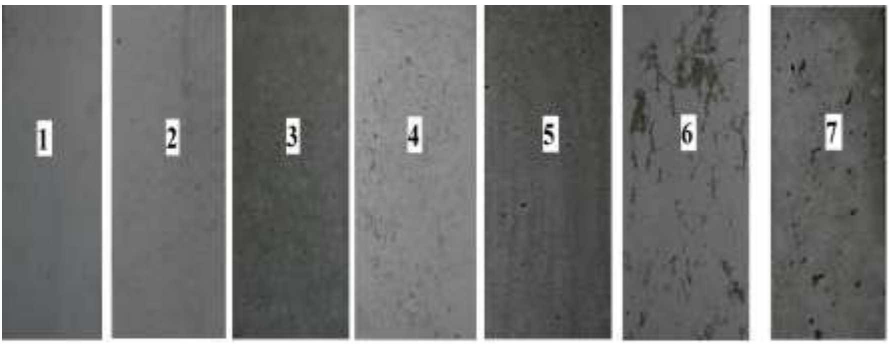


Fig. 21. The evaluation scale of the concrete surface quality obtained as the dissertation findings

These tests show the importance of the mixture's compaction on the formed concrete surface quality. It must be noted that yield stress as one of the mixture's rheological properties is closely connected with the mixture's technological property, specifically, the slump. Compaction, however, is denoted by straight dependence on the mixture's rheological property – its plastic viscosity.

CONCLUSIONS

1. On the grounds of systematic analysis of scholarly literature it can be concluded that there is lack of scientific information in terms of the conventional concrete mixture modification possibilities in order to obtain high quality surfaces. There is no commonly approved methodology in Lithuania which would allow to evaluate the quality of the produced concrete surfaces and to classify them. Most of the methods which are widely available are actually based on subjective opinion which is not a reliable factor which could enable us to classify surfaces according to their quality.
2. The image analysis method (software *BetongGUI 2.0*) easily allows to establish the quantity and the biggest dimension of the surface air pores. The produced concrete surfaces according to their quality levels can be classified by areas of blemishes in all the tested specimen.
3. The yield stress and plastic viscosity were significantly reduced by increasing the ratio of coarse and total mixture aggregate from 0.32 to 0.52. The surface blemishes sized 10 to 15 mm were reduced from 148 to 117 units while bigger defects measuring >15 mm were reduced from 96 to 37 units.
4. The increase of the fine particles (cement together with sand not exceeding 0.25 mm size) from 441 to 600 kg/m^3 significantly reduced the mixture's yield stress and its plastic viscosity. It also significantly reduced the ratio between the areas of surface blemishes and the total specimen size from 17.3 to 0 %.
5. An inclination of superplasticizer to 1.2 % of cement significantly reduced the mixture's yield stress and its plastic viscosity while the W/C ratio was steady. The ratio of blemishes was reduced from 0.37 % to 0.28 %. An increase of the viscosity modifying admixture up to 1.1 % did not significantly influence the mixture's rheological properties. On the other hand, it reduced the number of the differently sized surface blemishes. 10-15 mm blemishes were reduced from 157 to 14 units while >15 mm size defects were reduced from cases 44 to merely 1 unit.
6. An increase of the air entraining admixture resulted in the decreased yield stress and plastic viscosity values. It also had the positive influence on the formed concrete surface quality. This kind of admixture does not allow bigger pores to emerge while smaller pores are less visually noticeable. The utilization of air pores removing admixtures did not exhibit noticeable influence on the mixture's rheological properties although it reduced the

number of 10-15 mm sized air pores from 157 to 24 units and >15 mm pores from 44 to 3 units per 1 m^2.

7. The dependence between concrete surface blemishes and different constituents of the mixture can be expressed by a parabolic relation. Only the dependence between surface blemishes and the fine aggregate can be expressed according to an exponential dependence. Correlation coefficients in most cases show strong relations between the variables.
8. According to the obtained results, the mixture's slump cannot describe or somehow be linked with the formed concrete surface quality. The concrete surface quality is a factor combining many different variables: the quality and application of formwork; the type of form release agent and its quantity; the agent's application; the appropriate technology of mixture compaction and, finally, the human factor as well. It must be stressed that varying amounts and the types of mixture components maintain the biggest influence on the concrete surface quality.

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3. Research Council of Lithuania. Grant for a 3-month scientific internship in Norway, 2013.
4. "Erasmus" and "Erasmus+" grant for a scientific visit to Norway.
5. DAAD "German Academic Exchange Service". A grant for scientific internship in Germany for 3 months, 2014.

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Reziumė

Nustatyti modifikuoto įprastinio betono mišinio reologinių savybių įtaką betono paviršiaus kokybei taikant vaizdų analizės metodą.

Sprendžiami uždaviniai

1. Išanalizuoti smulkiųjų dalelių, smulkaus ir stambaus užpildų kiekio įtaką betono mišinio ribiniams šlyties įtempimams ir plastinei klampai bei patobulinti mišinio klampos apskaičiavimo formulę, įvedant klampos pokyčio koeficientą.
2. Pagal patobulintą paviršiaus kokybės vertinimo metodiką nustatyti įprastinio betono mišinio reologinių savybių įtaką paviršiaus kokybės vertinimo rodikliams.
3. Modifikuoti įprastinio betono mišinio sudėtį, įvertinus ryšį tarp mišinio reologinių savybių ir paviršinių oro porų kiekio bei jų pasiskirstymo dydžio nagrinėjamame plote.
4. Priskirti nagrinėjamus paviršius atskiroms klasėms pagal mišinio reologinių savybių įtaką paviršinių defektų santykiniam plotui.

Mokslinis darbo naujumas

Darbo mokslinį naujumą atspindi gauti šie statybos inžinerijos mokslui nauji rezultatai:

1. Patikslinta betono mišinio plastinės klampos skaičiavimo formulė, įvedant klampos pokyčio koeficientą.
2. Nustatytas didžiausią įtaką įprastinio betono mišinio reologinėms savybėms ir betono paviršiaus kokybei turintis smulkiųjų dalelių poveikis.
3. Ištirtas orą įtraukiančios įmaišos panaudojimo sumažinti paviršiaus defektų santykinį plotą efektyvumas.

Tyrimo metodai

Betono mišinių technologinės savybės nustatytos taikant standartinius bandymo metodus; įprastinio betono mišinio reologinės savybės apskaičiuotos naudojant literatūros šaltiniuose pateiktas formules; cemento tešlos plastinė klampa nustatyta rotaciniu viskozimetru Rheotest RN4; betono paviršiaus kokybė vertinta taikant vaizdų analizės metodą „BetonGUY 2.0“; betono paviršiai pagal kokybę suskirstyti į klases atsižvelgiant į GOST ir CIB Report keliamus reikalvimus.

IŠVADOS

1. Neaptikta literatūros šaltinių, kuriuose būtų analizuojamos Lietuvoje labiausiai paplitusios, įprastinių betono mišinių modifikavimo galimybės, siekiant išgauti tinkamą sukietėjusio betono paviršiaus kokybę. Taip pat nėra vienos bendros sistemos ar metodikos, kuri objektyviai leistų įvertinti betono paviršiaus kokybę. Beveik visos metodikos remiasi subjektyvia tyrėjo nuomone, apibūdinant vienokį ar kitokį kintamąjį, kuris yra reikalingas betono paviršiaus kokybei įvertinti.

2. Naudojant programinę įrangą „BetongGUY 2.0“ vaizdų analizės metodu nustatytas betono paviršinių oro porų kiekis pagal jų didžiausią matmenį. Gauti rezultatai perskaičiuoti į paviršinių defektų santykinį plotą ir remiantis užsienio literatūroje pateikta betono paviršiaus kokybės vertinimo skale, betono paviršiai pagal savo kokybę suskirstyti į atitinkamas klases pagal CIB report No. 24 bei GOST 13015.0-83 standartus.

3. Stambiojo užpildo santykį su bendru mišinio užpildo kiekiu įprastiniame betono mišinyje padidinus nuo 0,32 iki 0,52 ženkliai sumažėja mišinio ribiniai šlyties įtempiai bei plastinė klampa. 10-15 mm dydžio oro porų kiekis sumažėja nuo 148 iki 117 vnt., o didesnių kaip 15 mm oro porų kiekis sumažėja nuo 96 iki 37 vnt.

4. Smulkiųjų dalelių kiekio (cementas + smėlio dalelės iki 0,25 mm) padidinimas įprastiniame betono mišinyje nuo 441 iki 600 kg į 1m3 mišinio žymiai sumažina ne tik mišinio ribinius šlyties įtempius ir plastinę klampą, bet ir paviršinių defektų santykinį plotą nuo 17,3 iki 0 %.

5. Plastifikuojančios įmaišos polikarboksilato eterių polimerų pagrindu kiekio iki 1,2 % cemento masės padidinimas, esant pastoviam V/C santykiui, žymiai sumažina įprastinio betono mišinio ribinius šlyties įtempimus bei plastinę klampą. Paviršinių defektų santykinis plotas sumažėja nuo 0,37 iki 0,28 %. Klampą modifikuojančios įmaišos didelės molekulinės masės sintetinių kopolimerų pagrindu kiekio didinimas iki 1,1 % cemento masės žymesnės įtakos mišinio reologinėms savybėms neturi, tačiau 10-15 mm dydžio oro porų kiekį sumažina nuo 157 iki 14 vnt., o didesnių kaip 15 mm oro porų kiekis sumažėja nuo 44 iki 1 vnt.

6. Orą įtraukiančios įmaišos paviršių aktyvinančių medžiagų pagrindu kiekio didinimas % cemento masės ne tik sumažina įprastinio betono mišinio ribinius šlyties įtempius bei plastinę klampą, bet ir turi teigiamą įtaką betono paviršiaus kokybei. Mišinio klojimo bei tankinimo metu įmaiša neleidžia susiformuoti stambesnėms paviršinėms oro poroms, o smulkesnės yra mažiau pastebimos žmogaus akimi. Oro poras naikinančios įmaišos propoksilintų ir etoksilintų riebiųjų rūgščių pagrindu panaudojimas žymesnės įtakos įprastinio mišinio reologinėms savybėms neturi, tačiau 10-15 mm dydžio oro porų kiekį sumažina nuo 157 iki 24 vnt., o didesnių kaip 15 mm oro porų kiekis sumažėja nuo nuo 44 iki 3 vnt.

7. Ryšio forma tarp sukietėjusio betono paviršiuje susiformavusių oro porų kiekio ir įprastinio betono mišinio sudėties modifikavimui pasirinktų atskirų sudedamųjų dalių matematiškai gali būti aprašyta pagal parabolinę priklausomybę, išskyrus ryšio formą tarp oro porų kiekio ir santykio smulkiajame užpildų mišinyje tarp 0/1 bei 0/4 frakcijos smėlių kiekių, kuri matematiškai gali būti aprašyta pagal eksponentinę priklausomybę. Gautos

koreliacijos koeficientų reikšmės parodo, kad ryšys tarp kintamųjų kinta nuo silpno iki stipraus.

8. Nėra stebima bendra tendencija, kad pagal įprastinio betono mišinio technologinę savybę – slankumą būtų galima prognozuoti sukietėjusio betono paviršiaus kokybę. Į betono paviršiaus kokybę reikia žiūrėti kaip į kompleksinį procesą, kuriam įtakos turi naudojamų klojinių tipas, klojinių tepalo rūšis ir kiekis, mišinio klojimo ir tankinimo procesai, žmogiškasis veiksnys ir kita, tačiau didžiausią įtaką turi įprastinio betono mišinio sudėties modifikavimui pasirinktos atskiros mišinio sudedamosios dalys.

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