The influence of concrete mixture’s rheological properties on the quality of formed concrete surfaces

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Abstract. This study mainly lays emphasis on examining the influence of concrete mixture rheological properties on the quality of formed concrete surfaces. Mixture’s fine aggregate change was taken into the consideration. Over the course of concrete mixture preparation the inner ratio of fine aggregate (sand: fraction of 0/1 and 0/4) was changed. The idea was to increase the quantity of fine particles in the total aggregate’s volume therefore quantity of sand (fraction 0/1) was increased. Six different concrete mixture’s compositions were designed as well as three specimens (concrete piles of 1m² surface area) were casted. Rheological properties of concrete mixtures were analytically obtained and the quality of formed concrete surfaces was evaluated using image analysis method “BetonGUY 2.0”. As can be obtained from the dependence between concrete mixture rheological properties and its formed surface quality, the increase of concrete mixture’s yield stress and plastic viscosity reduces the quantity of air pores on formed concrete surfaces.

1. Introduction

Problems regarding concrete surface’s quality become very important because the demand of high level of aesthetics has spread across a wide variety of construction works [1]. Clients are no longer willing to accept poor quality structures which incur enormous repair and maintenance costs during the life-cycle of the building. It is obvious that producers of construction materials are offering many types of coatings for formed surfaces in order to achieve better appearance as well as durability characteristics [2-5]. The flatness of concrete surface is less important factor as long as it does not extremely exceed the certain limits. Tint and air bubbles are often a subject of conflict between owners, architects and building contractors as there are no strict national standards covering the problem [6]. A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning is one of the most recent designed to assess the quality of concrete surface [7]. This system, despite having a potential in subjective and reliable quality assessment of precast concrete elements can be hardly utilized. The method may be used only with precast elements in rectangular form also the thickness must be uniform. These factors result in a big limitation since concrete surfaces have complex geometries. Authors [8] offered 3 input parameters to assess the quality of concrete surface: bughole area; maximum bughole diameter; and bughole size distribution curve. This system proved to be effective in classifying the concrete surfaces depending on the degree of treatment required.

It must be noted that there are a lot of ways to improve concrete’s surface quality: suitable concrete mixture compositions, utilization of controlled-permeable formworks, correct usage of form release
agents, careful workmanship and decent vibration technology [9-10]. In order to obtain suitable concrete mixture compositions one should investigate its rheological properties. Scientists [11] presented the case that high quality concrete surfaces may be obtained with low values of plastic viscosity and yield stress for SCC concrete. Rheological properties are directly influenced by the constituents of concrete mixture [12-13]. Scientists [14] conducted a wide study on the influence of various mineral admixtures on rheological properties of self-compacting concrete. They put forward the fact that the ground granulated blast furnace slag can reduce the yield stress without resulting in the large decrease in plastic viscosity only up to 70%. Another study was conducted in order to improve concrete surface quality of precast concrete plant in Brazil. The subject of interest was the amount of surface honeycombs. Results showed that the increase of cement to 75% resulted in a significant decrease of their size and number. However the different type of form release agent that was used did not show a significant influence on surface quality. There are some recommendations on concrete surface’s evaluation but most of them leave plenty of room for subjective appreciation. Concrete Innovation Centre (COIN) is currently working on the tool which would provide an objective evaluation of formed surface’s quality. The tool covers grey scale and distribution of pores. These two main parameters of concrete surface’s quality must be evaluated separately.

This study was carried out due to the important questions raised whether the rheological properties of concrete mixture influence the formed concrete surface quality. The authors of this research assed the significant of fine aggregate usage as one of the main methods to change the rheological properties of concrete mixture. The dependence between concrete mixture’s rheological properties and its formed surface quality was also taken into the consideration. Norwegian evaluation methodology of concrete surfaces was used as the main frame [15].

2. Materials and methodology

JSC “Akmenes cementas” (Lithuania) Portland cement CEM II/A-LL 42.5 R was used for the test. Physical and mechanical properties of Portland cement are presented in Table 1.

| Property                          | Value |
|----------------------------------|-------|
| Specific surface area, m²/kg     | 410   |
| Particle density, kg/m³          | 3.05  |
| Normal consistency of cement paste, % | 26.5  |
| Volume stability, mm             | 0.8   |
| Initial setting time, min.       | 195   |
| Compressive strength after 2 days / 28 days, MPa | 27.1 / 54.0 |
| Loss on ignition, %              | 5.05  |
| Insoluble materials, %           | -     |
| SO₃, %                           | 2.48  |
| Cl⁻, %                           | 0.015 |
| Alkalis, calculated by Na₂O equivalent, % | <0.8 |

Sand from “Kvesu” quarry fraction 0/1 and 0/4, bulk densities 1520 kg/m³ and 1710 kg/m³ and fineness modules 1.78 and 2.62 was used as fine aggregates. Gravel fraction 4/16 and bulk density 1327 kg/m³ was used as the coarse aggregate. Granulometric composition of aggregates is conducted according to LST EN 12620 and presented in Table 2.

Superplasticizer Glenium SKY 628 based on polycarboxylate (BASF „Construction Chemicals Italia Spa“) was used as plasticizing admixture. The density of solution 1.06 kg/l, yellow liquid. The total dosage of admixture was 1.2% of cement.
Concrete mixtures were mixed for 3 minutes in the laboratory in forced type concrete mixer. Only dry aggregates were used for concrete mixtures. Cement and aggregates were dosed by weight while on the other hand, water and chemical admixtures were dosed by volume. 90% of water was instantly poured to the mix. Plasticizing admixture was mixed with 10% of remaining water and poured into the mixer. Remaining admixtures were dozed directly to the mix.

The slump of concrete mixture was determined according to standard LST EN 12350-2, the density according to standard LST EN 12350-6 and the air content according to standard LST EN 12350-7.

Concrete mixture’s rheological property yield stress was evaluated according to equation (1). Yield stress of non-vibrated concrete mixture can be calculated according to its fresh technological parameters: density and slump [16]. This equation is adjusted according to standard cone which is used to evaluate the slump of concrete mixture.

\[
\tau_0 = \frac{0.00815 \cdot \rho_m}{\left(0.498 + \frac{0.001724}{\sqrt{30 - SL} - 0.024}\right)}
\]  

(1)

here: \(\tau_0\) – yield stress of concrete mixture, Pa; \(\rho_m\) – density of concrete mixture, kg/m³; \(SL\) – slump of concrete mixture, cm.

Second mixture’s rheological property – plastic viscosity was evaluated according to equation (2). Plastic viscosity is established by concentration of aggregates which are used in concrete mixture.

\[
\eta_p = \eta_v \cdot \exp \left( \frac{a \cdot \rho_v}{\rho_c} \cdot \left( \frac{1 - \phi_v - \phi_c - \frac{V \cdot C}{\rho_v \cdot \rho_c}}{1 - \phi_v - \phi_c - \frac{V \cdot C}{\rho_v \cdot \rho_c}} \right) + \frac{a \cdot \phi_v}{\rho_c} \cdot \left( \frac{1 - \phi_v - \phi_c - \frac{V \cdot C}{\rho_v \cdot \rho_c}}{1 - \phi_v - \phi_c - \frac{V \cdot C}{\rho_v \cdot \rho_c}} \right) \right)
\]  

(2)

here: \(\phi_v\) – air content of concrete mixture, %; \(V, C\) – water and cement quantities in concrete mixture (1 m³); \(\rho_v, \rho_c\) – densities of water and cement, kg/m³; \(\phi_{sm}, \phi_{st}\) – volume concentration of fine aggregate in

**Table 2. Granulometric composition of aggregates**

| Diameter of the sieve’s mesh, mm | The amount of poured out material, % |
|----------------------------------|-------------------------------------|
|                                  | Sand fraction 0/1 | Sand fraction 0/4 | Gravel fraction 4/16 |
| 16.0                             | 100.00            | 100.00            | 98.80                 |
| 8.0                              | 100.00            | 100.00            | 42.10                 |
| 4.0                              | 100.00            | 95.10             | 4.30                  |
| 2.0                              | 99.80             | 81.80             | 1.00                  |
| 1.0                              | 99.10             | 54.60             | 0.52                  |
| 0.500                            | 77.40             | 12.40             | 0.44                  |
| 0.250                            | 2.20              | 0.70              | 0.36                  |
| 0.125                            | 0.50              | 0.30              | 0.32                  |
| 0.000                            | 0.00              | 0.00              | 0.00                  |
mortar and coarse aggregate in concrete mixture; \( a_c, a_{sm}, a_{st} \) – factors describing the form of cement, fine and coarse aggregate’s particles \( (a_c = 2.6; a_{sm} = 2.5; a_{st} = 2.6) \); \( b_c, b_{sm}, b_{st} \) – factors describing the density distribution of cement, fine and coarse aggregate respectively in mortar and concrete mixture.

It is utmost important to assess the significance of concrete casting process. PERI LM0303S formwork system (Figure 1a) was used to hold the concrete mixture. Formwork’s surface (plywood) was carefully cleaned after the application of form release agent Rheofinish 218 (BASF „Construction Chemicals Italia Spa“). The consolidation of concrete mixture was not taken into the consideration therefore the method and time of vibration was not changed (internal vibrator, 6 seconds). In order to evaluate the quality of formed concrete rectangular columns \((1.2 \times 0.2 \times 0.2 \, \text{m})\) were casted (Figure 1b). Each side of the column was divided into two separate regions \((0.6 \times 0.2 \times 0.2 \, \text{m})\). The average results of 4 different surfaces of each concrete specimens were evaluated in this study.

![Figure 1. Formwork system (a) and formed concrete rectangular columns (b)](image)

High-end photography equipment was used for this study. All pictures were taken by Nikon D3200 with 24 megapixels camera. The lens Nikon DX AF-S NIKKOR 18-55 mm was used to improve quality of the images. Separate mounted flashlight “Quantuum” was also used. Sensor’s parameters: max resolution – 6016 \times 4000; image ratio w:h – 3:2; effective pixels – 24 megapixels; sensor photo detectors – 25 megapixels; sensor size – APS-C \((23.2 \times 15.4 \, \text{mm})\).

The parameters of image taking equipment used in this study: aperture, 8 F; shutter speed, 1/160 s; flash intensity, 15 GN; ISO number 100. Figure 2 indicates the positioning of image taking equipment.

![Figure 2. Positioning of image taking equipment (1- flash light; 2- camera; 3- concrete surface)](image)

Flash equipment had to be moved in both sides (left and right) in respect to camera’s position in order to get the best possible illumination (shadows) of surface bubbles. Firstly, it had to be moved to the left and secondly to the right side in 450 towards the testing surface. It must be noted that a distance between the surface and the camera should not exceed 70 cm in order to get height quality images. After that the quality of formed concrete surfaces was evaluated using image analysis method “BetonGUY 2.0”. The main parameters for evaluation of surface quality were the number of air pores per 1m² and
their size. Air pores were classified not only by their quantity but by biggest dimensions as well: 1-5 mm, 5-10 mm, 10-15 mm and bigger than 15 mm. The biggest attention was paid to bigger air pores: 10-15 mm and >15 mm. Bigger pores are more noticeable from the distance and therefore more important in terms of assessing the quality of formed concrete surface.

3. Results and discussions
In order to evaluate the influence of fine aggregate – sand (fraction 0/1) quantity to the technological and rheological properties of concrete mixtures, the quantity of sand (fraction 0/1) was increased while the quantity of sand (fraction 0/4) was decreased. The quantity of sand (fraction 0/1) was changed from 11 to 36% according to mass in respect to total fine aggregates quantity. The compositions of concrete mixtures (BA1-0 – BA1-5) used in this research are presented in Table 3.

Table 3. Compositions of concrete mixture

| Materials               | Unit | Concrete mixture compositions. Amount of materials for 1m³ of concrete mixture |
|-------------------------|------|--------------------------------------------------------------------------------|
|                         |      | BA1-0   | BA1-1 | BA1-2  | BA1-3  | BA1-4  | BA1-5  |
| Portland cement         | kg   | 330     | 330   | 330    | 330    | 330    | 330    |
| Water                   | l    | 178     | 178   | 178    | 178    | 178    | 178    |
| Gravel fraction 4/16    | kg   | 986     | 986   | 986    | 986    | 986    | 986    |
| Sand fraction 0/4 (%)   |       | 701     | 607   | 512    | 417    | 322    | 227    |
| Sand fraction 0/1 (%)   |       | 208     | 303   | 398    | 493    | 588    | 682    |
| Superplasticizer        | l    | 3.74    | 3.74  | 3.74   | 3.74   | 3.74   | 3.74   |
| Water and cement ratio  | –    | 0.54    | 0.54  | 0.54   | 0.54   | 0.54   | 0.54   |

As there is shown at Table 4, with the increase of sand (fraction 0/1) quantity from 11 to 36%, the slump of concrete mixture decreases from S4 to S3 class according to LST EN 12350-2 standard. To sum up, the slump of concrete mixture reduces about 1.03. By increasing the quantity of fine aggregate, surface area increases. In order to keep the mixture’s consistency at the same level, the liquid phase must be increased. The highest values of concrete mixture slump (~270 mm) was obtained with the usage of 11 % of 0/1 fraction sand.

Table 4. Technological properties of concrete mixtures

| Technological property | Unit | Value of technological property of concrete mixture |
|-----------------------|------|----------------------------------------------------|
|                       |      | BA1-0 | BA1-1 | BA1-2 | BA1-3 | BA1-4 | BA1-5 |
| Density               | kg/m³| 2380  | 2310  | 2330  | 2310  | 2310  | 2320  |
| Slump                 | mm   | 270   | 260   | 260   | 250   | 250   | 200   |
| Air content           | %    | 4.5   | 4.3   | 4.1   | 4.1   | 4.5   | 4.9   |

The density of concrete mixture decreases while increasing the quantity of fine aggregate (sand, fraction 0/1) from 11 to 36%. On the other hand, the air content slightly increases. The density of concrete mixture varies from 2380 to 2320 kg/m³, while air content – from 4.5 to 4.9%. The lowest air content rate (~4.1 %) was obtained with the usage of 21-26% of 0/1 fraction sand.

The dependence between concrete mixture’s composition and its rheological properties is presented in Figure 3.
It is obvious that plastic viscosity increased by about 1.8 when the quantity of fine aggregate was increased from 11 to 16%. Further increase of fine aggregate’s quantity did not have a significant influence on plastic viscosity. On the other hand, yield stress constantly increased while increasing the quantity of fine aggregate from 11 to 31%. Yield stress significant increased while increasing the quantity of fine aggregate from 31 to 36%.

The influence of sand (fraction 0/1) quantity on formed concrete surface quality was established by 3 specimens formed of different concrete mixtures. Three different quantities of fine aggregate were chosen according to previously established rheological properties: 11% – reference point with the lowest quantity; 16% – an intermediate point with medium quantity; 31% – limit point with the biggest quantity. Following graphs show the ratio between area of surface air pores and total specimen’s area, which named Ap/As. Figure 4 presents the dependence between mixture’s rheological properties and area of surface air pores and total specimen’s area while changing the quantity of fraction 0/1 sand. As can be obtained from Figure 4, the quantity of surface air pores per 1 m² significantly declined by increasing the yield stress (Figure 4a) and plastic viscosity (Figure 4b). Despite the further decrease of surface air pores, the optimal ratio between 0/1 mm and 0/4 mm fractioned sand was 0.5. The bigger ratio resulted in a stiff mixture which was not technological to work with. It must be noted that vibration was not taken into the consideration while preparing concrete mixtures. This is another very important factor and should be covered in more detail in future researches.

Figure 3. The dependence between mixture’s composition and rheological properties: yield stress (a) and viscosity (b)

Figure 4. The dependence between mixture’s yield stress (a), plastic viscosity (b) and area of surface air pores and total specimen’s area (Ap/As)
Provided mixture’s parameters give the perfect insight on the dependence between rheological properties and number of surface air pores. The optimal concrete mixture composition was found to be BA1-1 with the values of yield stress – 180.54 Pa and plastic viscosity – 1.764 Pa.s. Yield stress and plastic viscosity values were found to be increased while increasing the amount of fine aggregate. With increased amount of fine aggregate, water demand became higher and therefore concrete mixtures became stiffer. To sum up, the stiffer concrete mixture is, more power is needed in order to initiate the material’s flow (yield stress) and to keep that flow going (plastic viscosity).

Figure 5 shows how formed concrete’s surface quality had changed. It indicates the distribution of differently sized concrete surface air pores. The increase of fine aggregate from 208 kg to 588 kg per 1 m³ of concrete mixture reduced the number of surface air pores: 1÷5 mm reduced by 2.7 times; 5÷10 mm by 8.3 times and > 15 mm reduced by 51 times. The conclusions can be drawn that more fine aggregate (more fine particles) are added the higher quality of concrete surface can be expected.

![Figure 5](image-url)

**Figure 5.** The influence of quantity of fine aggregate on the formed concrete surface air pores number: 1-5 mm and 5-10 mm (a); 10-15 mm and >15 mm (b)

The best dependence of dispersion of values of concrete mixtures composition and formed concrete surface air pores number is presented in Figure 5. Equations of dispersion of the results, empirical and correlation coefficients values are presented in Table 5. Correlation coefficient (Pearson), which is evaluating the strength of linear relationship, was calculated according to coefficient of empirical equation. The closer correlation coefficient is to 1, the better representation of the dispersion of values in the curve. According to the obtained correlation coefficient, it was determined which equation describes the best distribution of statistical data.

| Size of surface air pores, mm | Equation | Coefficients value of equation | R-squared value | Correlation coefficient |
|------------------------------|----------|--------------------------------|----------------|-------------------------|
| 1-5                          | \(y = ax^2 - bx + c\) | \(a = 44.080\) \(b = 2217.5\) \(c = 30626\) | 1.0 | 1.0 |
| 5-10                         | \(y = ax^2 - bx + c\) | \(a = 9.2600\) \(b = 435.25\) \(c = 5279.3\) | 1.0 | 1.0 |
| 10-15                        | \(y = ax^2 - bx + c\) | \(a = 2.1754\) \(b = 107.14\) \(c = 1274.0\) | 1.0 | 1.0 |
| >15                          | \(y = ax^2 - bx + c\) | \(a = 2.5967\) \(b = 124.10\) \(c = 1357.8\) | 1.0 | 1.0 |

The dispersion of values of dependence of concrete mixture composition on the quantity of concrete surface air pores could be described by a polynomial dependency. The calculated values of correlation
coefficients are 1.0. It shows, that variables are statistically dependent and based on values of correlation coefficients – the relationship between variables is very strong.

The results of this study revealed that more fluid concrete mixtures with more fine particles (within normal workability limits) provides higher surface quality. The air content of concrete mixture is widely questionable in terms of concrete surface’s quality. Air content of concrete mixture falls into two main categories: entrapped air and entrained air. Entrapped air is a type of air bubbles which appears in the concrete mixture during the casting process or vibration. The second type of air appears due to the usage of air entraining admixtures. It is obvious that more entrapped air in the concrete mixture is, the lower concrete surface quality, due to air pores, is obtained. The usage of air entraining agents raises important questions whether it can reduce the amount of entrapped air in concrete mixture and thus to improve concrete surface’s quality. Scientists put forward the argument that the utilization of air entraining admixture results in reordering of the entrapped air bubbles (bigger ones) due to the micro air pores which are entrained in the concrete mixture by using certain. In this way, bigger entrapped air pores reach the surface of the formwork and escape easier [17-19]. On the other hand, scientists briefly summarize that the utilization of air entraining admixtures results in lower values of concrete mixture’s yield stress and this factor has the tendency to worsen the quality of formed concrete surface.

As can be obtained from the dependence between concrete mixture rheological properties and its formed surface quality, the increase of concrete mixture’s yield stress and plastic viscosity reduces the number of surface air pores. It is obvious that bigger amount of fine aggregate results in better concrete surface quality.

4. Conclusions

- The digital software “BetonGUY 2.0” enables to evaluate the influence of different concrete mixture’s components on the quantity and size distribution of formed surface air pores.
- The increase of concrete mixture’s yield stress and plastic viscosity reduces the quantity of air pores on formed concrete surfaces. The research was carried out with sand as fine aggregate.
- The increase of fine aggregate from 208 kg to 588 kg per 1 m$^3$ of concrete mixture reduced the number of surface air pores: 1÷5 mm reduced by 2.7 times; 5÷10 mm by 5.8 times; 10÷15 mm by 8.3 times and > 15 mm reduced by 51 times.
- Based on this study it can be concluded that the most significant surface’s air pores fall into two main categories: 5÷10 mm and > 15 mm. This is due to the fact that bigger pores are clearly visible and recognized from the reasonable distance and therefore they have the biggest influence on surface quality.

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