Consideration of the characteristics of the concrete mix when choosing concrete pump

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Abstract. The industry produces a large number of concrete pumps of different projects with a wide range of characteristics. Relevant is the problem of selecting the concrete with the required characteristics. The Construction Department of the Kaliningrad State Technical University has conducted studies of the characteristics of stationary concrete pumps. The main steps in the selection of concrete pump have been validated: plotting the pressure generated by a pump, from its feeding; the construction of the dependence of hydraulic losses in the hose from the flow of the mixture; determining characteristics of the concrete mixture; determining the operating point of the pump unit; verify the adequacy of the supply of the concrete pump. The dependence of the pressure generated by the investigated concrete pump may be divided into 3 sections: the horizontal line segment, the parabola, the sloping line. The empirical relationship for hydraulic losses was used. It is shown how the characteristics of the studied concrete mixtures affect the operating point. Concrete mixtures were divided into two sets. The decrease in the average size of the filler leads to an increase in productivity of concrete pump. The growth of cement per 1 m$^3$ of concrete mix leads to a decrease in performance of the pump. The proposed algorithm allows calculate the necessary characteristics for selection of the concrete pump under given conditions of construction.

1. Introduction
Modern construction technologies widely use concrete pumps. A promising direction is the use of building printers for 3D printing houses [1]. The industry produces a large number of pumps of different projects with a wide range of characteristics [2-5]. For example, table 1 lists the technical characteristics of three samples of stationary concrete pumps produced in Germany.

Table 1. Technical characteristics of stationary concrete pumps [4]

| Model            | BSA 1409 D | BSA 2108 HPE | BSA 14000 HPD |
|------------------|------------|--------------|---------------|
| Output rodside   | 97 m$^3$/h | 79 m$^3$/h   | 82 m$^3$/h    |
| Pressure rodside | 7.1 MPa    | 15.0 MPa     | 18.5 MPa      |
| Strokes rodside  | 37/min     | 20/min       | 26/min        |
| Output pistonside| 67 m$^3$/h | 55 m$^3$/h   | 54 m$^3$/h    |
| Pressure pistonside | 10.6 MPa | 22.0 MPa     | 26.0 MPa      |
| Strokes pistonside | 25/min   | 14/min       | 18/min        |
| Delivery cylinder diameter | 200 mm   | 200 mm       | 180 mm       |
Relevant is the problem of selecting the concrete with the required characteristics. It is known that max output and max pressure cannot be achieved simultaneously. There are many publications on the pumping of concrete. The study focuses on the rheological characteristics of concrete mixtures (for example, [6-8]) and the hydraulic losses in the hose (for example, [9-10]). Much less published are articles on the study of concrete pumps themselves and the pumping units (concrete pump – hose). Selection of concrete pump using the superiority and inferiority ranking method was considered in [11]. While the actual working conditions of the pump system are not taken into account. This situation complicates the choice of such a pump, which would correspond to construction conditions.

The construction faculty of the Kaliningrad state technical University has conducted studies of the characteristics of stationary concrete pumps. Development of methodology for selection of the characteristics of the concrete pump is one of the important areas of research [12]. The purpose of this article is to study the influence of the concrete mix parameters at the operating point pumping system and selection of the necessary characteristics of the concrete pump.

2. Analysis charts of the performance of concrete pumps

Performance charts of concrete pumps, as a rule, is submitted by their manufacturers [2-5]. The dependence of the pressure generated by the investigated concrete pump, its flow \( f(Q) \) may be divided into sections: the first function is a horizontal line segment, the second – best approximated by a parabola, the third by a segment of sloping line, as formula (1).

\[
P = f(Q) = \begin{cases} 
P_1 & \text{if } Q < Q_1; \\
P_2 - \alpha \cdot Q + \beta \cdot Q^2 & \text{if } Q_1 \leq Q \leq Q_2; \\
P_3 - c \cdot Q & \text{if } Q_2 < Q < Q_3. 
\end{cases}
\]  

An example of concrete pump chart of the performance of PC 506D Italian Company CIFA is shown in figure 1. The empirical coefficients in equation (1) were calculated by the method of least squares. Curves obtained for concrete pumps of other brands and manufacturers differ only by coefficients. The values of the coefficients for the four models of stationary concrete pumps are presented in table 2.

| Delivery cylinder stroke | 1400 mm | 2100 mm | 2100 mm |
|--------------------------|---------|---------|---------|
| Drive Power              | 140 kW  | 250 kW  | 470 kW  |

![Figure 1](image.png)

**Figure 1.** Performance diagram of concrete pump PC-506D Italian Company CIFA. Points are experimental data [2], the line is the result of the calculation by the formula (1).
3. Hydraulic losses in the concrete hose

Hydraulic losses in the pipeline depend on the value of specific resistance to movement of the concrete mix, the total length of the hose and the magnitude of its vertical section, as well as local pressure losses in the transition cone and knees. The theoretical model is not too reliable. We use the empirical dependence for the hydraulic losses of [13], taking into account modern systems of units:

\[
\Delta P = \varphi(Q) = \frac{4(L + h)}{d} \cdot (\tau_0 + b \cdot V(Q)) + \gamma \cdot g \cdot h, \quad V = \frac{4 \cdot Q}{\pi \cdot d^2},
\]

where \(\Delta P\) is the loss of pressure on the transportation of a mixture of hose (Pa); \(L\) is given (calculated) length of the horizontal pipeline (m); \(d\) is inner diameter of hose (m); \(\gamma\) is volumetric weight of concrete (kg/m\(^3\)); \(V\) is the mean (flow) velocity of the mixture (m/s); \(\tau_0\) is the ultimate shear stress of concrete mix (Pa); \(g\) is acceleration of free fall (m/s\(^2\)); \(h\) is height of the concrete mix flow (m); \(b\) is the speed coefficient (Pa·s/m).

In [13] \(L\) is recommended for detection of the actual length of tubing \(L_0\) to add on a 1 m horizontal flow of the mixture for every 10° rotation of the hose. For example, suppose that the total hose length \(L_0 = 87\) m, the number of bends 90° in the hose is equal to 7 pieces. Then the given length of the pipeline will be \(L = 87 + 90 \cdot 7/10 = 150\) m.

4. Characteristics of the concrete mixture

Within the boundaries of adobepremiere concrete mixture, critical shear stress and the velocity ratio depends on the following factors: water-cement ratio, cement consumption, fineness of cement, the grain shape of aggregates, the proportion of fine particles in the aggregate mix. The values of \(\tau_0\) and \(b\) decrease with increasing water-cement ratio, the grain size of the cement, in the proportion of small particles in the mixture of fillers and the round shape of the grains of the latter. With the increase of cement consumption value \(\tau_0\) decreases and \(b\) increases. In [13] mixtures are not structured. It is advisable to split them into two sets as in table. 3. The main feature of the first set is change of granulometric composition of the filler at a constant flow of cement per 1 m\(^3\) of the concrete mixture. The main feature of the second set is change of the cement consumption per 1 m\(^3\) of the concrete mixture and the ratio water/cement at a constant granulometric composition of the filler.

| Table 2. Empirical coefficients for the four samples of concrete pumps |
|---------------------------------------------------------------|
| **Empirical coefficients** | **Schwing Stetter (UK) [5]** | **Italian Company CIFA [2]** |
| \(Q_1\) (m\(^3\)/h) | 18.0 | 46.2 | 15.7 | 23.8 |
| \(Q_2\) (m\(^3\)/h) | 49.8 | 72.2 | 32.7 | 52.8 |
| \(Q_3\) (m\(^3\)/h) | 51.8 | 73.3 | 34.0 | 53.9 |
| \(P_1\) (MPa) | 7.60 | 6.50 | 9.10 | 5.70 |
| \(P_2\) (MPa) | 13.95 | 15.51 | 21.09 | 11.82 |
| \(P_3\) (MPa) | 73.04 | 291.9 | 106.7 | 122.5 |
| \(\alpha\) (MPa h/m\(^3\)) | 0.429 | 0.268 | 1.01 | 0.332 |
| \(\beta\) (MPa h\(^3\)/m\(^6\)) | 0.00415 | 0.00158 | 0.0150 | 0.00297 |
| \(c\) (MPa h/m\(^3\)) | 1.41 | 3.98 | 3.14 | 2.27 |
| Index mix | Consumption of cement (per 1 m$^3$ of concrete mix) | The ratio Water/Cement | Mixture volume weight | Mass-average aggregate size |
|-----------|---------------------------------------------------|------------------------|-----------------------|-----------------------------|
| A        | 300 kg/m$^3$                                      | First set              | 2400 kg/m$^3$         | 12.0 mm                     |
| B        | 300 kg/m$^3$                                      | 0.54                   | 2390 kg/m$^3$         | 10.9 mm                     |
| C        | 300 kg/m$^3$                                      | 0.54                   | 2400 kg/m$^3$         | 9.6 mm                      |
| E        | 300 kg/m$^3$                                      | 0.63                   | 2360 kg/m$^3$         | 8.1 mm                      |
| F        | 220 kg/m$^3$                                      | 0.87                   | 2360 kg/m$^3$         | 9.85 mm                     |
| G        | 270 kg/m$^3$                                      | 0.65                   | 2370 kg/m$^3$         | 9.85 mm                     |
| J        | 300 kg/m$^3$                                      | 0.62                   | 2360 kg/m$^3$         | 9.85 mm                     |
| H        | 350 kg/m$^3$                                      | 0.51                   | 2370 kg/m$^3$         | 9.85 mm                     |

There are experimental data $\tau_0$ and $b$ in [13] at different values of the concrete slump ($C_S$, cm) for common mixtures. We have found that these dependencies can be approximated by polynomials of the third order (3) with an error of less than 4 %.

$$\tau_0(C_S) = t_0 + t_1 \cdot C_S + t_2 \cdot C_S^2 + t_3 \cdot C_S^3, \quad b(C_S) = b_0 + b_1 \cdot C_S + b_2 \cdot C_S^2 + b_3 \cdot C_S^3. \quad (3)$$

Figure 2 as an example shows that the calculation results by formulas (3) are in good agreement with the experimental data of the concrete mix A.

**Figure 2.** Dependence of the limiting shear stress and velocity ratio from the slump of the concrete mix A. Points are data from [13], lines are calculation results by formulas (3).

The practice of building increases the production of concrete mixes modified with various additives. Their rheological properties can significantly differ from the formulas (3) and figure 2 [14, 15].

**5. Operating point of the pump system**

The operating point of each pumping system has been found by numerical solution of the equation $\phi(Q) = f(Q)$. Figures 3 and 4 show the results of calculating the following parameter values $C_S = 6$ cm; $d = 0.1$ m; $L = 150$ m. The performance of the concrete pump decreases with increasing height $h$ (figure 3). So at the height of 40 m PC-506D CIFA will pump 31.96 m$^3$/h concrete mix E (pressure at the outlet of the pump 4.244 MPa) and at the height of 100 m only 23.64 m$^3$/h (pressure 5.633 MPa).
The decrease in the average size of the filler 12 to 8.1 mm under given conditions leads to an increase in productivity of concrete pump from 23.64 almost up to 32 m$^3$/hour (figure 4). The pressure at the outlet of the pump is reduced 5.686 MPa to 4.244.

The growth of cement from 220 to 350 kg per 1 m$^3$ of concrete mix leads to a decrease in performance of concrete pump from 28.83 to 24.28 m$^3$/hour (figure 5). The pressure at the outlet of the pump increases 4.718 to 5.509 MPa.

Check of the adequacy of the performance of concrete pump is an important phase of selection. It is also possible to give the cost characteristics of the concrete pumps in the selection, but this is a topic of separate research.

**Figure 3.** Determining the operating point of the pumping unit concrete mixture E and different $h$; 1 – performance diagram of concrete pump PC-506D CIFA; 2-5 – hydraulic losses in the hose: 2 – $h = 40$ m; 3 – $h = 60$ m, 4 – $h = 80$ m, 5 – $h = 100$ m

**Figure 4.** Determining the operating point of the pumping unit at $h = 40$ m and different concrete mixtures; 1 – performance diagram of concrete pump PC-506D CIFA; A, B, C, E – hydraulic losses in the hose (the index of the mixture at the table 3)
Figure 5. Determining the operating point of the pumping unit for different concrete mixtures; F, G, H – hydraulic losses in the hose (the index of the mixture at the table 3). Working conditions are the same as in figure 4.

6. Conclusions

Thus, the developed method of calculation allows to consider not only the hydraulic characteristics of discharge pipe (length, height, pressure loss), but the performance graph of the concrete pump. Characteristics of the concrete mix affect the operating point of the pump system. The decrease in the average size of the filler under given conditions leads to an increase in productivity of the concrete pump. The growth of cement per 1 m$^3$ of concrete mix leads to a decrease in performance of the concrete pump. The proposed algorithm allows to calculate the necessary characteristics for selection of the concrete pump under given conditions of construction. Characteristics of modern concrete mixtures require further experimental and theoretical studies.

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