The influence of aggregates type on W/C ratio on the strength and other properties of concrete

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Abstract. The influence of different types of aggregates and W/C ratio on concrete properties is analysed. In order to achieve this aim, lightweight (with expanded clay aggregate) and normal concrete (with gravel aggregate) mixtures are prepared with different W/C ratios. Different W/C ratios are selected by reducing the amount of cement when the amount of water is constant. The following properties of concrete have been determined: density, compressive strength and water absorption. Additionally, the statistical data analysis is performed and influence of aggregate type and W/C ratio on concrete properties is determined. The empirical equations indicating dependence between concrete strength and W/C and strength of aggregate are obtained for normal concrete and light-weight concrete.

1. Introduction
The quality of the concrete products and structures is determined by its properties. Numerous researches have been conducted around the world, and they have confirmed its heterogeneity. This fact significantly complicates the working process as well as manufacturing of concrete products and constructions.

The special attention should be paid to designing of concrete composition and methods for prediction of properties depending on different parameters with the aim of obtaining a material with given characteristics. The main properties that determine the performance and durability of concrete are porosity, density, water absorption and strength.

The strength of concrete is one of the most important properties of concrete which depends on several parameters. Today, there are many theories, empirical formulas, and methods dedicated for the prediction of strength for different types of concrete. It is considered to be that Feret, Abrams, Bolomey, Skramtav are the founders of these theories [1, 2].

In accordance with the Abrams' law (1), a key parameter in determining concrete strength is the ratio of water/cement:

$$\sigma_c = A/B^{W/C}$$ (1)

where $\sigma_c$ - compressive strength, W/C - water to cement ratio, A, B - constants which are dependent on given material, age and test conditions.
Along with Abrams' law, the Bolomey's formula is widely used. It takes into account the dependence of strength not only on the water to cement ratio but the degree of hydration as well [3, 4] (2):

$$\sigma_c = k_1 \left( \frac{1}{W/C} - k_2 \right)$$  \hspace{1cm} (2)

where $\sigma_c$ - compressive strength, $W/C$ - water to cement ratio, $k_1$ - parameter dependent on concrete composition and degree of hydration, $k_2$ - constant parameter.

These laws allow the effective prediction of the strength characteristics of concrete, however, contemporary researchers introduce some refinements in order to obtain the most accurate computational models. Mainly, optimization of existing laws of the concrete strength is linked to the fact that the strength depends not only on water to cement ratio, but also the chemical composition of the binder, properties of aggregates, cement to aggregate ratio and features of interfacial zone between cement and aggregates.

Researchers [4] have studied the performance of Abrams' law for cement mortar. In the course of the study Abrams' generalized law for mortars ranging from very low strength to very high strength was obtained.

The influence of water to cement ratio combined with a cement to sand proportions on compressive strength is also presented in [5]. The applicability of the Abrams’ law is proved and the optimal water to cement ratio is determined. It is equal to 0.5 when changing the ratio of cement to sand to 1:3, 1:4, 1:5, 1:6, 1:7, 1:8.

M. C. Nataraja and M. C. Sanjay have demonstrated the implementation of generalized Abrams’ law and modified Bolomey equation for the design of concrete based on cement, river sand as fine and broken stone soap granite as coarse aggregates. The calculated deviation of the strength values obtained in the course of the experiment on the basis of Abrams’ and Bolomey laws are no more than 5 % [6].

The number of scientific works of contemporary researchers are devoted to ascertain the influence of aggregate on the strength of the light, normal and high performance concrete [7–16].

Thus, in the study [7], the effect on durability of lightweight concrete aggregate such as expanded clay with different grades - 25, 15, 5 mm at different water to cement ratios has been studied. The greatest strength is achieved for aggregates with the size of 15 mm.

The use of crushed limestone as a coarse aggregate for normal strength concrete determines the increase in strength up to 12 % [8].

Influence of coarse aggregate on durability of high strength concrete is estimated in [9]. Three types of coarse aggregates such as siliceous round gravel, crushed limestone and crushed basalt have been taken for the experiment. The strength of the samples with gravel on 28th day is by (10–20) % lower than that of the samples with limestone and basalt.

The attention should be paid to the fineness of the cement and its chemical composition when the prediction of the strength properties of concrete is desirable.

T. S. Nagaraj and Z. Banu have established the dependence on the basis of the Abrams' law. It takes into account the synergistic effect of concrete components (3) [17]:

$$\frac{S}{S_{0,5}} = A + B \left( \frac{1}{W/C} \right)$$  \hspace{1cm} (3)

where $S$ - the compressive strength; $S_{0,5}$ - compressive strength for $W/C = 0.5$; $W/C$ - water to cement ratio; $A$, $B$ – constant parameters.

Along with the water to cement ratio, properties of aggregates and binder, the porosity influences the strength of concrete. K. S. Pann and others have obtained the mathematical model for the dependence
of the strength of the concrete on water to cement ratio and capillary porosity. The basis of the mathematical relation is the Abrams' law (4):

$$f_c' = \frac{A}{BWC} + C/DPC$$

where $f_c'$ - the compressive strength of concrete on 28th day; A, B, C and D - empirical constants, W/C - water to cement ratio, PC - calculated capillary porosity. The mathematical model provides with sufficiently accurate solutions and, consequently, it can accurately predict the strength of designed concrete [18].

The influence of water to cement ratio and porosity on strength properties of concrete is measured in the work of the authors [19]. It is found that when water to cement ratio changes from 0.45 to 0.60, the porosity increases to 150 % and strength reduces by 75.6 %.

The pore structure is an important property in determining the quality of concrete. It has an impact not only on strength, but also on transport properties and durability [20]. Researchers [21] have obtained the model for predicting the freeze-thaw resistance on the basis of control parameters such as capillary porosity, water to cement ratio, air content, curing time and etc. The resulting model has shown sufficient accuracy in the prediction of the freeze-thaw resistance of concrete what makes it possible to be applied in practice.

The analysis of the works of contemporary researchers has confirmed the impact on concrete quality of number of factors such as water to cement ratio, properties of binders and aggregates, their proportions in the material volume, pore distribution and etc. They have obtained the mathematical models allowing sufficient accuracy for the prediction of strength and durability of concrete. However, the issue is not fully understood and requires further research.

Scientists [22] have tested high performance concretes with gravel aggregates as coarse aggregate which W/C varies from 0.28 to 0.55. It is determined that dependence of compressive, tensile and bending strengths of high performance concrete on W/C ratio may be linearly approximated.

The purpose of this study is to obtain empirical equations describing the influence of aggregate type and water to cement ratio on the strength characteristics of concrete and other properties such as density and water absorption.

2. Materials and methods

Portland cement CEM I 52.5 R which conforms the requirements of EN 197-1 was used. The main characteristics of Portland cement are presented in Table 1 (results obtained from manufacturers).

| Designation   | Bulk density, kg/m³ | Specific gravity, kg/m³ | Compressive strength after 7 days, MPa | Compressive strength after 28 days, MPa |
|---------------|---------------------|-------------------------|----------------------------------------|----------------------------------------|
| CEM I 52.5 R  | 1250                | 3150                    | 55                                      | 62                                      |

Coarse aggregate - gravel conforms the requirements of EN 12620. Fraction 4/16. The weak strain content (sandstone, limestone and etc.) is no more than 2 % (from manufacturers). The tests of aggregates are carried out based on EN 1097-2, EN 1097-3, EN 1367-2, EN 933-1 and EN 1097-2. Research data on physical and mechanical properties of gravel are presented in Table 2. Compressive strength of gravel and expanded clay is determined according to EN 1097-11 by compressing 20 mm of the specimen height.
Table 2. Research data on physical and mechanical properties of gravel (fraction 4/16).

| Characteristic              | Tests results |
|----------------------------|---------------|
| Particle density, kg/m³    | 2650          |
| Water absorption, %        | 1.30          |
| Bulk density, kg/m³        | 1546          |
| Compressive strength, MPa  | 47.2          |

Fine aggregate - sand conforms the requirements of EN 12620. Fraction 0/4. Research data on physical properties of sand are presented in Table 3.

Table 3. Physical properties of sand.

| Characteristic              | Tests results |
|----------------------------|---------------|
| Particle density, kg/m³    | 2600          |
| Water absorption, %        | 0.59          |
| Bulk density, kg/m³        | 1640          |

Properties of expanded clay conforming the requirements of EN 14063 are presented in Table 4.

Table 4. Properties of expanded clay.

| Characteristic              | Fraction         | Tests |
|----------------------------|------------------|-------|
| Bulk density, kg/m³        | 4/8              | 290   |
| Bulk density, kg/m³        | 8/16             | 250   |
| Particle density, kg/m³    | 4/16             | 410   |
| Water absorption after 24 h, % | 4/16         | 17.5  |
| Compressive strength, MPa  | 4/8              | 1.97  |
| Compressive strength, MPa  | 8/16             | 1.11  |
| Compressive strength, MPa  | 4/16 (mixture, 50 wt. % each) | 1.39  |

Technological additive - superplasticizer Dynamon XTend conforms the requirements of EN 934-2. Water conforming the requirements of EN 1008 used for the experiments.

Composition and density (determined according to EN 12350-6) as well as slump (determined according to EN 12350-2) of concrete mixtures are presented in Table 5. First 6 mixtures have been mixed with lightweight aggregate (expanded clay) and designated as LC, other mixtures have been mixed with coarse aggregate - gravel. Expanded clay before mixing was about 1 h saturated in water. The main difference between mixtures is different W/C ratio which varies from 0.3 to 0.8. While changing W/C ratio, the amount of cement has reduced and the amount of water has remained the same. Moreover, in order to maintain the same density of concrete, the reduced amount of cement has been compensated with fine aggregate. After determination of concrete mixtures' density, compositions have been re-calculated.

Table 5. Compositions of concrete mixtures.

| Designation | Composition of concrete, kg/m³ | Mix density, kg/m³ |
|-------------|-------------------------------|--------------------|
|             | Cement, kg/m³ | Gravel 4/16, kg/m³ | Sand, kg/m³ | Expanded clay 4/16, kg/m³ | Water, kg/m³ | Plasticizer, kg/m³ | W/C | Mix density, kg/m³ |
| LC1         | 506              | 0                  | 666          | 233              | 152          | 5.06                | 0.3 | 1563               |
| LC2         | 377              | 0                  | 795          | 233              | 152          | 3.77                | 0.4 | 1583               |
| LC3         | 304              | 0                  | 868          | 233              | 152          | 3.04                | 0.5 | 1594               |
It is seen from the data presented in Table 5 that the density of concrete mixture depending on the W/C ratio changes only slightly. When lightweight aggregate is used, the density of mixture increases with the increase in W/C ratio, and after addition of gravel, the density of mixture remains the same.

(100x100x100) mm sized specimens formed from the prepared mixtures have been maintained for 1 day under normal conditions, and after that - 27 days in water which temperature is 20 °C. Production and hardening of concrete specimens for determination of compressive strength is carried out according to EN 12390-2. Compressive strength of specimens is determined based on EN 12390-3. Density - in accordance with EN 12390-7. Water absorption – on the basis of literature [23].

Grouping and preparation of data for the regression analysis are carried out using “Microsoft Excel” and “Statistica” software. Statistical analysis of the obtained physical-mechanical and structural parameters is conducted according to literature [24–29]. The pattern of relation is tested by applying following function types: linear \( y = a + bx \), quadratic \( y = a + bx^2 \), power law \( y = ax^b \), exponential \( y = ab^x \) and etc. For the determination of mathematical relation, the selection of a function is based on accurate description of distribution nature and multidimensional correlation and determination coefficients which are close to 1. Multidimensional correlation coefficient is described as square root of determination coefficient \( R^2 \), and it has negative value in the case of negative regression and positive - in the case of positive regression. It is clear that \( 0 \leq R^2 \leq 1 \), when \( R^2 \) is closer to one, it is assumed that selected regression curve is the most suitable for description of experimental data. For example, when \( R^2 = 0.8 \), it may be concluded that 80 % of \( y \) values are described by independent variable \( x \).

3. Tests Results and Analysis

Slump dependence of concrete mixture on W/C ratio is shown in Fig. 1. It can be observed that increasing W/C ratio reduces slump when both types of aggregates are used, i.e. lightweight aggregate and gravel. In both cases, slump has reduced by approximately 50 %. The reduction in slump may be explained by reduced amount of plasticizer. The amount of plasticizer has been reduced due to reduced amount of cement. The chosen amount of plasticizer is 1 % by cement mass.

![Figure 1. Slump dependence of concrete mixtures on W/C ratio.](image-url)
The density of specimens is determined after 28 days of concrete hardening. The results are presented in Table 6.

It can be seen from Table 6 that W/C ratio has low impact on concrete density, the density is reduced by 4.6 % when expanded clay aggregate is used, and by 3.8 % - when gravel as aggregate is used. The reduction in density may be explained by the amount of cement having the specific gravity of 3150 kg/m3 which has been changed by the amount of sand having the particle density of 2600 kg/m3 (respectively, Table 1 and Table 3).

### Table 6. The results of concrete density.

| Characteristic                      | W/C=0.3 | W/C=0.4 | W/C=0.5 | W/C=0.6 | W/C=0.7 | W/C=0.8 |
|-------------------------------------|---------|---------|---------|---------|---------|---------|
| Density of concrete with lightweight aggregate, kg/m³ | 1592    | 1577    | 1559    | 1539    | 1530    | 1519    |
| Density of concrete with coarse aggregate, kg/m³ | 2443    | 2419    | 2392    | 2407    | 2386    | 2350    |

The greatest impact on density has the density of used aggregates: bulk density of gravel is approximately 1400 kg/m³, particles density is 2650 kg/m³ (Table 2), and expanded clay - bulk density is 270 kg/m³, particles density is 410 kg/m³ (Table 4).

After measurement and weighting of specimens, compressive strength after 28 days of concrete hardening is determined. The compressive strength dependence on W/C ratio is presented in Fig. 2.

[Figure 2. Compressive strength dependence on W/C ratio when lightweight aggregate is used (a) and compressive strength dependence on W/C ratio when gravel is used (b).]

It can be observed from the presented results that compressive strength gradually reduces according to W/C ratio law when W/C ratio increases.

The empirical equation according to which compressive strength of concrete ($f_c$) can be predicted by assessing the strength of an aggregate ($f_a$) (determined based on EN 1097-11 when specimens are compressed 20 mm by height) and W/C ratio of mixture is concluded:

$$f_c = 32.8 + \frac{13.2}{W} - \frac{60.4}{f_a}$$

(5)

Statistical indicators of empirical equation (5) are presented in Table 7. The curve of data distribution according to the obtained empirical equation is presented in Fig. 3.
It can be seen from Table 7 that the relationship between analysed indicators is very strong, multidimensional correlation coefficient of the equation is 0.939. Student’s criteria show the significance of the indicators. All indicators are rather higher that the value of Student’s criterion which is presented in statistical table (when 36 specimens are tested under significance level of 0.05, Student’s criterion in statistical table is approximately 2.0). According to the values of Student’s criterion, the greatest impact in compressive strength has the strength of an aggregate and only then W/C ratio which is significant as well.

**Table 7.** Statistical indicators of empirical equation (5).

| Correlation coefficient | Determination coefficient | Student’s criteria |
|-------------------------|---------------------------|--------------------|
| 0.939                   | 0.882                     | 6.87               |
|                         |                           | 6.49               |
|                         |                           | 14.4               |

This equation may be used for the prediction of compressive strength after 28 days of concrete hardening when W/C ratio varies from 0.3 to 0.8, and compressive strength of aggregates ranging from 1 MPa to 50 MPa is determined based on EN 1097. Fig. 4 shows how much strength is reduced when W/C ratio ranging from 0.3 to 0.8 and different aggregates are used.

**Fig. 3.** Compressive strength dependence on W/C ratio and the strength of an aggregate.

**Fig. 4.** Compressive strength losses dependence on W/C ratio and aggregate type.
The change in compressive strength depending on W/C ratio is sufficiently high: using gravel, the strength reduced by 60 % when W/C ratio increases from 0.3 to 0.8, using lightweight aggregate - by approx. 30 %.

Fig. 5 shows how water absorption changes depending on W/C ratio and aggregate type. Water absorption of concrete is mainly dependent on aggregate type. When gravel is used, water absorption after 24 h is observed to be approx. 4 %, when expanded clay is used, it has changed approximately from 6 % to 13 %.

![Figure 5. Water absorption dependence on W/C ratio and aggregate type.](image)

Water absorption of concrete with gravel as an aggregate is only slightly dependent on W/C ratio. It may be explained by the fact that water absorption of gravel is 1.3 % and it does not change much over time. Water absorption of expanded clay after 24 h of immersion is 17.5 %. Water absorption curves of gravel as an aggregate when W/C ratio varies from 0.3 to 0.8 almost touch each other; although, when expanded clay is used, the impact of W/C ratio is significant because dried specimens are measured. Dried specimens have open pores where water easily penetrates into lightweight aggregate, and it is worth to mention that an increase in W/C ratio increases open porosity of concrete as well. The lowest water absorption is obtained when W/C ratio is 0.3. In the range of 0.3 and 0.8 of W/C ratio, water absorption after 24 h of immersion when expanded clay is used as an aggregate has increased by approx. 100 %.

4. Conclusions
It is determined that slump of concrete mixture reduces when W/C ratio increases even though the same amount of water is used in the mixtures; however, when the amount of cement is reduced, the amount of plasticizer has been reduced as well what has the greatest impact on slump value. 

W/C ratio does not have a great influence on density of concrete. The density W/C ratio increases from 0.3 to 0.8 reduces by approximately 4 % when both types of aggregates are used, i.e. lightweight aggregate and gravel.

Compressive strength changes according to hyperbolic function what conforms Abram’s law for W/C ratio, the correlation coefficient of the obtained equation is 0.939. The most significant impact on compressive strength according to concluded empirical equation has the strength of an aggregate, W/C ratio remains significant as well.
Comparing with normal concrete, water absorption of concrete with lightweight aggregate is significantly higher when W/C ratio is the same due to higher water absorption of expanded clay and increased open porosity of cement stone when W/C ratio increases.

References
[1] Bazhenov Y 1975 Methods of determining the composition of the concrete of various kinds (Moscow: Strojizdat) p 268
[2] Larrard F 1999 Concrete mixture proportioning: a scientific approach p 427
[3] Nielsen L 1993 Mater Struct 26 255–60
[4] Appa G 2001 Cem Concr Res 31 495–502
[5] Singh S, Munjal P, Thammishetti N 2015 J Build Eng 4 94–100
[6] Nataraja M, Sanjay M 2013 J Civ Eng 41 (1) 59–69
[7] Tommy Y, Tang W, Cui H 2007 Build Environ 42 3025–29
[8] Meddah M, Zitouni S, Belaabes S 2010 Constr Build Mater 24 505–12
[9] Oz turf T, Cecen C 1997 Cem Concr Res 27 165–170
[10] Haach V, Vasconcelos G, Lourenco P 2011 Constr Build Mater 25 2980–87
[11] Banu Z, Nagaraj T 1996 Constr Build Mater 10(4) 251–53
[12] Bogas J, Gomes A 2013 Materials and Design 46 832–41
[13] Dilli M, Atahan H, Sengul C 2015 Constr Build Mater 101 260–67
[14] Cui H, Lo T, Memonb S, Xu W 2012 Constr Build Mater 35 149–58
[15] Beshr H, Almusallam A, Maslehuddin M 2003 Constr Build Mater 17 97–103
[16] Beushausen H, Dittmer T 2015 Constr Build Mater 74 132–39
[17] Nagaraj T, Banu Z 1996 Cem Concr Res 26 (6) 933–42
[18] Pann K, Yen T, Tang C, Lin T 2003 Aci Materials Journal 100(4) 1–23
[19] Kim Y, Lee K, Bang J, Kwon S 2014 Adv Mater Sci Eng 1–12
[20] Chen X, Wu S 2013 Constr Build Mater 38 804–12
[21] Skripkiunas G, Vaitkevicius V, Dauksys M, Grinys A 2008 Proc Int Conf Scotland 317–324
[22] Skripkiūnas G, Navickas A, Vaitkevičius V 1997 Proc Int Conf Lithuania 21–24
[23] Mačiulaitis, R 1996 Frost resistance and durability of facade bricks. Frostwiderstand und Dauerhaftigkeit keramischer Fassadenerzeugnisse. Fasadinės keramikos atsparumas šalčiui ir ilgaamžiškumam (Vilnius: Technika) p 132
[24] Čekanavičius V, Murauskas G 2002 Statistics II and application (Vilnius: TEV) p 268
[25] Mantia A 2001 Teorija veroyatnostej i matematicheskaja statistika: Uchebnoe posobie (Moskva: Izdat. отд. УНЦ ДО) p 120
[26] Ostle B, Turner J, Hicks C, Elrath G 1996 Engineering statistics. The Industrial Experience. (Belmont, California: Wadsworth Publishing Company) p 568
[27] Kleinbaum D, Kupper L, Muller K, Niram A 1998 Statistical analysis (Brooks/Cole Publishing Company) p 798
[28] Graybill F, Iyer H 1994 Regression analysis (Belmont, California: Wadsworth Publishing Company) p 701
[29] Sheikin A, Chehovskij J, Brusser M 1989 Portlandcement concrete with high frost resistance (Leningrad: Stroiizdat) p 128
[30] Sakalauskas V 2003 Analysis with Statistica (Vilnius: Margi raštai) p 227