INFLUENȚA VOLUMULUI DE PASTĂ ŞI A GRANULAȚIEI AGREGATULUI ASUPRA CONSISTENȚEI ŞI REZISTENȚEI LA COMPRESIUNE A BETONULUI
CONCRETE CONSISTENCY AND COMPRESSIVE STRENGTH DEPENDENCY ON THE QUANTITY OF CEMENT PASTE AMONG THE AGGREGATE GRAINS

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The mechanical and rheological properties of concrete depend to a great extent upon the type of realized structure which can be viewed from the aspect of the relationship of the space between the grains in the aggregate and the quantity of the the cement paste in the concrete. The influence of the degree of filling of the cavities in the aggregate with the paste (k_e) on the consistency type has to view in the light of the realized structure of concrete taking into consideration the particle size distribution and water-cement ratio. Generally, with the increase of the degree of filling of the cavities in the aggregate with the cement paste from 0.9 to 2.5 the consistency of concrete changes from stiff to very fluid. The maximum values of compressive strength are realized when the degree of filling of the cavities in the aggregate that can be considered as optimal is within the relatively narrow limits, and then the value of the parameter ranges between 1.2 to 1.4.

Proprietățile mecanice şi reologice ale betonului depind în mare măsură de spațiul sau volumul intergranular şi de volumul de pastă de ciment , corelat cu acesta. Gradul de umplere al volumului intergranular cu pastă (k_e) influențează consistența betonului, în corelație cu distribuția granulomertrică a agregatului şi cu raportul apă-ciment. În general, creşterea gradului de umplere a spațiilor intergranulare din volumul de agregat, cu pastă de ciment, la un coeficient de umplere de la 0,9 la 2,5 se corelează cu modificarea consistenței betonului de la starea de beton vârtos la cea de beton foarte fluid. Valorile cele mai mari ale rezistenței la compresiune se obțin la atingerea unui grad optimal de umplere cu pastă a volumului intergranular al agregatului. Conform datelor experimentale, acesta aparține unui domeniu de valori ale parametrului de umplere destul de îngust, între 1,2 şi 1,4 .

Keywords: *cement paste, aggregate, concrete, rheologic properties, mechanical properties*

1. Introduction

Durability and resistance to the atmospheric influence are the characteristics that are almost regularly required in concrete and concrete structures. In that aspect, the compact, well-composed concrete, produced from the good quality components has the advantage over other types of concrete. It is known that the characteristics of concrete depend on the realised structure of the ratio of the aggregate and cement paste in concrete [1-3].

Regarding this issue, the very voluminous researches of the influence of the degree of filling of the space between the aggregate grains with the cement paste on the certain characteristics fresh and hardened concrete have been done in the building materials laboratory at the Faculty of Civil Engineering and Architecture of Nis, Serbia. In this paper, only a part relating to the change of consistency and compressive strength will be shown. A special attention has been paid to the realised concrete structure, i.e. its compactness.

Three different types of fresh concrete structure can be discerned, depending on the relation of the cement paste quantity and aggregate. The diagram of these structures is shown in figure 1 [2].

In the structure 1, the cement paste is predominant. The aggregate grains are significantly divided with the paste so that it can be considered that there is no interaction of the grains [4]. The grains have influence only in the zone of contact with the paste and the magnitude of the influence is directly dependent on the specific surface of the grain. Such concrete mixtures most frequently have good fluidity and can easily be built in.

Structure 2, as a rule, enables production of the very compact concrete. It is one of the main prerequisites for obtaining of a hardened concrete of the required quality. At a concrete corresponding structure 2, the amount of cement paste is smaller in respect of the structure 1, but there is enough of it to fill in the space between the aggregate grains and to separate them slightly [1-2]. Concrete with such structure are more difficult to build in, in respect of the concrete mixtures of the previous

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type. In order to reduce their viscosity and increase fluidity it is necessary to expose them, during the building in, to the action of the certain external influences which cause such effects (such as vibration) [5].

In the structure 3, the aggregate is dominating. The cement paste enfolds the aggregate grains with a thin film, but there is no enough of it to fill in all the space between the grains [6]. The friction effect is far more prominent than in the structure 2 and the fluidity of such mixtures is almost negligible. During the building in of such mixtures, very often the special technological procedures are required [7, 8].

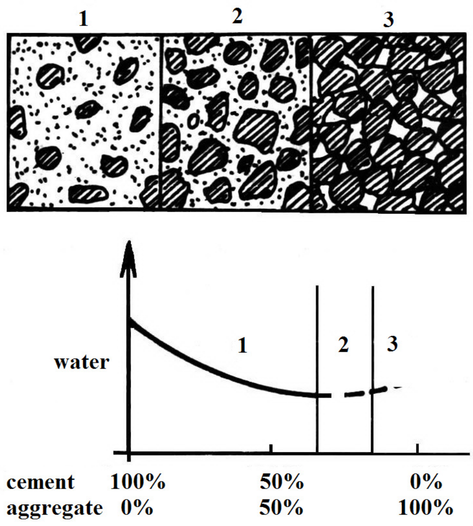

Fig. 1 – Types of fresh concrete structures/ *Structuri de beton proaspăt.*

The main objective of the research presented in this paper was to determine what effects the degree of filling of the space between the aggregate grains (by cement paste) have on the consistency and compressive strength of concrete. In order to accomplish this, an extensive experimental research has been done, which provided a sufficient number of results and the appropriate range of results. The obtained results have been analyzed by the mathematical statistics methods, and some dependencies having high degree of correlation have been obtained, which is presented in the following chapters.

2. Experimental work

2.1. Material used in the experiment

Only one brand of cement was used for production of concrete, this being Holcim PC 20S 42.5N (CEM II/A-S), which met all the quality requirements according to the Serbian national standard SRPS EN 197-1. In the experimental work, a separated river aggregate from the Southern Morava river has been used, divided in four fractions: 0/4, 4/8, 8/16 and 16/31.5 mm. The aggregate met all the quality requirements prescribed by the national standard SRPS B.B2.010 [9]. The particle size distribution of aggregate fractions is given in table 1.

Particle size distribution of aggregates for production of concrete were designed with: "AS", "ABS" and "BS". The mixture "AS" was selected so that, to a greatest extent possible, considering the particle size distribution of the fractions, it corresponded to the aggregate "A", and the composed mixture "BS" so that it corresponded to the aggregate "B". The third mixture "ABS" was selected so that it's grading curve takes the median path of the area bordered by the grading curves "A" and "B". Particle size distribution and composed mixtures of the aggregate were given in the table 2 and figure 2.

Table 1

Particle size distribution of aggregate/*Granulozitatea agregatului*

Aggregate fraction *Clasa granulară* [mm]	Sieve dimension/ *Latura ochiului sitei* [mm]											
	0.125	0.25	0.5	0.71	1	2	4	8	11.2	16	22.4	31.5
0/4	0*	7	26	49	65	92	100	-	-	-	-	-
4/8	0*	1	1	1	2	5	20	97	100	-	-	-
8/16	0	0	0	1	1	1	1	25	89	100	-	-
16/31.5	0	0	0	0	1	1	1	1	2	21	85	100

Table 2

Aggregate mix particle size distribution as sieve passing / *Granulozitatea amestecurilor de agregat folosite în beton*

Aggregate mix used for concrete/*Tipul de agregat folosit în beton*	Sieve passing percentage/*Trecere prin sită , în procente:*							
	0.25 mm	0.5 mm	1 mm	2 mm	4 mm	8 mm	16 mm	31.5 mm
A	2	5	8	14	23	38	62	100
B	8	18	28	37	47	62	80	100
AS	1.3	4.5	11.8	16.8	20.8	39.4	62.9	100
ABS	2.2	7.5	19.1	27.3	32.5	51.9	72.6	100
BS	3.2	11.6	29.3	41.6	47.2	62.1	80.2	100

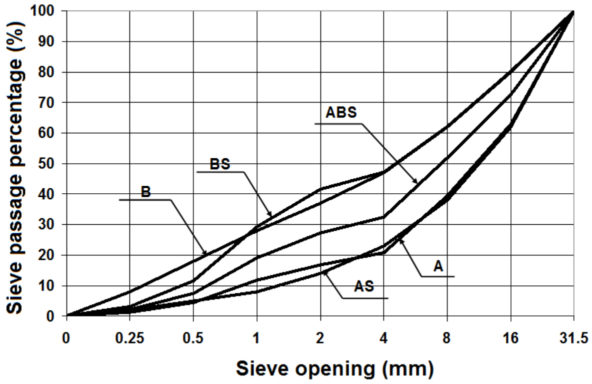

Fig. 2 – Particle size distribution curves of aggregates/*Curbe de distribuție granulometrică a agregatelor.*

No admixtures have been used for production of concrete.

2.2 Concrete mixtures types

When composing concrete mixtures, it was an aim to obtain as wide a spectre of different composition as possible, in respect to the granulometric composition, amount of cement and water/cement ratio. For each of three different particle size distributions ("AS", "ABS" and "BS") the amount of cement was varied from 250 to 500 kg for 1m^3 of concrete in 50 kg steps.

Three water/cement ratios 0.46, 0.52 and 0.58 (designations 1, 2 and 3 in the recipes) were

Table 3

Concrete mixes prepared with the "AS" aggregate/*Betoane preparate cu agregat "AS"*

No. *Nr.*	Mix design *Cod beton*	Cement *Ciment* m_c [kg]	Aggr. *Agregat* m_c [kg]	Water *Apă* m_v [kg]	$\omega_c = m_v/m_c$	Vebe Time/*Timp Vebe* [sec]	Mass ratio *Raport masic* m_a/m_c	Compressive strength ($f_{p,c}$) after: *Rezistența la compresiune după:* 3 days *zile*	7 days *zile*	28 days *zile*	90 days *zile*
1	A1/300	316	1894	145	0.46	14	6.00	26.3	31.3	36.4	42.1
2	A1/350	365	1876	168	0.46	11	5.14	27.1	34.0	40.9	47.9
3	A1/400	404	1817	186	0.46	6	4.50	26.2	35.9	47.2	53.2
4	A1/450	440	1762	203	0.46	3	4.00	25.2	33.3	44.0	52.9
5	A1/500	471	1695	217	0.46	2	3.60	22.6	31.6	42.9	50.8
6	A2/250	269	1938	140	0.52	23	7.20	19.6	25.4	34.2	38.9
7	A2/300	321	1927	167	0.52	8	6.00	21.5	28.9	38.4	44.9
8	A2/350	361	1855	188	0.52	5	5.14	22.1	29.4	39.9	47.1
9	A2/400	398	1789	207	0.52	4	4.50	21.9	30.9	40.6	46.8
10	A2/450	432	1730	225	0.52	1	4.00	19.1	27.3	36.9	43.7
11	A2/500	458	1650	238	0.52	< 1	3.60	18.7	27.1	36.7	42.4
12	A3/250	273	1966	158	0.58	8	7.20	19.2	25.0	35.6	40.1
13	A3/300	316	1897	183	0.58	6	6.00	19.8	27.3	37.0	43.2
14	A3/350	355	1824	206	0.58	3	5.14	18.6	25.5	36.7	42.3
15	A3/400	388	1747	225	0.58	1	4.50	14.7	22.7	34.2	39.7
16	A3/450	418	1672	242	0.58	< 1	4.00	13.3	20.6	31.5	37.4

Table 4

Concrete mixes prepared with the "ABS" aggregate / *Betoane preparate cu agregat "ABS"*

No. *Nr.*	Mix design *Cod beton*	Cement *Ciment* mc [kg]	Aggr. *Agregat* mc [kg]	Water *Apă* mv [kg]	ωc = mv/mc	Vebe Time *Timp Vebe* [sec]	Mass ratio *Raport masic* ma/mc	Compressive strength (fp,c) after: *Rezistența la compresiune după:* 3 days *zile*	7 days *zile*	28 days *zile*	90 days *zile*
1	AB1/250	272	1959	125	0.46	35	7.20	19.6	24.6	33.6	36.1
2	AB1/300	325	1950	150	0.46	13	6.00	24.7	35.4	47.0	54.9
3	AB1/350	366	1882	168	0.46	7	5.14	23.1	33.3	45.3	54.6
4	AB1/400	402	1811	185	0.46	3	4.50	19.7	34.1	43.6	52.1
5	AB1/450	437	1748	201	0.46	2	4.00	19.7	35.6	47.0	56.2
6	AB1/500	468	1685	215	0.46	1	3.60	16.0	33.3	43.9	49.8
7	AB2/250	276	1987	146	0.52	19	7.20	18.0	25.4	36.2	43.4
8	AB2/300	320	1919	169	0.52	7	6.00	20.4	31.0	44.1	53.3
9	AB2/350	360	1852	191	0.52	3	5.14	20.0	28.7	43.1	52.2
10	AB2/400	396	1782	210	0.52	1	4.50	15.6	25.5	41.0	48.7
11	AB2/450	430	1719	223	0.52	< 1	4.00	14.7	24.6	40.1	47.5
12	AB2/500	461	1659	240	0.52	< 1	3.60	13.0	23.7	38.1	46.1
13	AB3/250	276	1985	160	0.58	8	7.20	17.0	27.8	41.7	52.0
14	AB3/300	316	1898	184	0.58	3	6.00	16.7	26.4	39.8	49.2
15	AB3/350	354	1817	205	0.58	1	5.14	16.9	26.4	40.7	48.3
16	AB3/400	388	1744	225	0.58	< 1	4.50	12.9	23.4	36.2	44.8
17	AB3/450	420	1678	243	0.58	< 1	4.00	9.6	20.4	33.3	40.0

Table 5

Concrete mixes prepared with the "BS" aggregate / *Betoane preparate cu agregat "BS"*

No. *Nr.*	Mix design *Cod beton*	Cemen *Ciment* m_c [kg]	Aggr. Agregat m_c [kg]	Water *Apă* m_v [kg]	$\omega_c = m_v/m_c$	Vebe Time *Timp Vebe* [sec]	Mass ratio *Raport masic* m_a/m_c	Compressive strength ($f_{p,c}$) after: *Rezistența la compresiune după:*			
								3 days *zile*	7 days *zile*	28 days *zile*	90 days *zile*
1	B1/300	316	1895	145	0.46	54	6.00	26.7	32.9	43.9	48.0
2	B1/350	362	1860	166	0.46	19	5.14	28.9	36.5	48.5	56.1
3	B1/400	398	1793	183	0.46	8	4.50	27.3	36.6	47□6	53.1
4	B1/450	432	1729	199	0.46	3	4.00	25.7	35.0	46.6	53.7
5	B1/500	463	1668	213	0.46	< 1	3.60	22.0	30.2	42.4	49.7
6	B2/300	317	1902	165	0.52	17	6.00	24.9	33.6	45.5	51.6
7	B2/350	355	1825	185	0.52	6	5.14	24.0	32.0	43.9	51.8
8	B2/400	390	1753	203	0.52	3	4.50	23.0	30.4	42.7	48.6
9	B2/450	423	1692	220	0.52	1	4.00	21.6	29.4	41.4	48.0
10	B2/500	459	1653	239	0.52	< 1	3.60	20.3	28.7	40.4	46.6
11	B3/250	269	1938	156	0.58	27	7.20	20.4	30.4	41.2	46.1
12	B3/300	311	1864	180	0.58	9	6.00	19.4	28.6	40.0	46.5
13	B3/350	347	1783	201	0.58	2	5.14	17.7	25.9	37.8	45.1
14	B3/400	383	1722	222	0.58	1	4.50	17.0	24.1	35.8	41.9
15	B3/450	414	1655	240	0.58	< 1	4.00	13.9	19.8	31.5	36.8

varied for each possible previous combination. In such a way, 49 various compositions of concrete were made, and all three possible cases referring to the mutual relationship of the cement paste volume and space volume between the aggregate grains were covered. In other words, it was possible to analyze the characteristics of each previously described concrete structure.

The actual consumption of material for production of 1 m^3 of concrete is given in tables 3 for concretes with AS aggregate, 4 for concretes with ABS aggregate and 5 for concretes with BS aggregate (columns 3-5). In these table are presented the values of consistency (column 7) that was measured by Vebe apparatus according to the SRPS ISO 4110 [10] standard and the compressive strength values after 3, 7, 28 and 90 days (columns 9-12) that were determined according to the SRPS ISO 4012 standard [11].

2.3. Experimental determination of space volume between the aggregate grains

Apart from the possible theoretical calculation of the space volume between the aggregate grains used for the making of concrete is measured experimentally. For that purpose, the equipment as in figure 3 was used.

A transparent plexiglas cover (3) was fixed with a suitable joint (3) to a cylindrical vessel (1), 224 mm in diameter and 9.79 dm^3 in volume. In order to remove the air bubbles during the test, the cover was slightly bent upwards. The elastic rubber ring provided the water-tightness. A thin transparent tube of 3 mm inner diameter (5) was placed in the centre of the cover with a mark (6) on it, to whose level the water was poured during the tests. The volume of the vessel measured to the

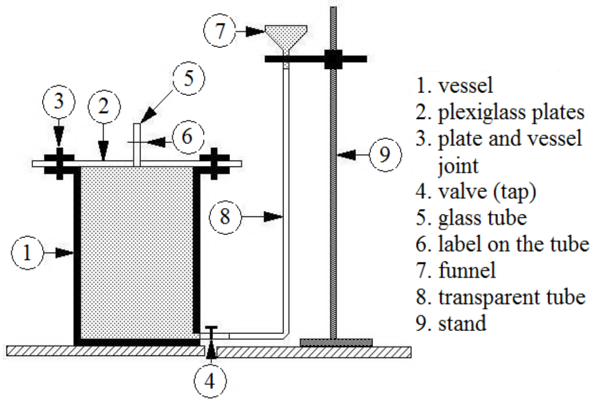

Fig. 3 – Equipment for measuring of the space volume between the grains in the aggregate /*Instalația experimentală pentru măsurarea volumului de goluri al agregatului.*

mark (6) is 9.95 dm^3. The vessel was filled with water from below, through a tap (4) which is connected to the glass funnel (7) (where the water was poured), by a transparent tube (8). The mass of the equipment, with all the integral parts from (1) through (8) was 5.380 kg.

The space volume between the aggregate grains was determined with the aid of this equipment, for each mixture used for concrete making. Before measuring, the aggregate was dried to the constant mass at 105±5 °C. The vessel was filled with the aggregate in three layers and each layer was compacted by piercing with a metal rod. The mass of a filled vessel was measured, and then the vessel was filled with water to the mark on the glass tube and the mass was measured again. The difference of the pre-vious measurements represents the mass of poured water. In the further procedure the water was let out through the tap at the bottom of the vessel

Table 6

The results of the determination of space volume in the aggregate (%)
Rezultatele determinării volumului de goluri din agregat (%)

Aggreg.code *Cod agregat*	Mass of dry aggregate *Masa agregatului uscat* [kg]	Density of compact. aggreg./ *Densitatea în grămadă îndesată a agreg.* [kg/m^3]	Mass of vessel with aggreg. and water *Masa recipientului cu agregat şi apă* [kg]	Mass of poured water *Masa apei introduse în recipientul cu agregat* [kg]	Mass of discharge. Water *Masa apei extrase* [kg]	Mass of water for Aggregate moisturiz. *Masa apei de umectare agregat* [kg]	Percent. of moisturize. water *Apa de umectare* [%]	Space in aggreg. exper. *Volumul de goluri obținut experim.* $\alpha_{a,exp}$ [%]
AS	18.67	1910	26.60	2.39	1.73	0.66	3.54	24.41
ABS	19.02	1945	26.69	2.13	1.32	0.82	4.28	21.76
BS	19.16	1960	26.66	1.96	0.76	1.20	6.26	20.02

into a graduated measure. In such a way the data about the quantity of water used for moistening of the grain surface was acquired, and the result is that a far less quantity is used for the capillary absorption by the aggregate grains. The obtained data were shown in table 6.

3. Discussion of the results

3.1 The influence of the degree of filling of the space between the aggregate grains with the cement paste on a consistency

Here the so-called structural concept of the understanding of concrete is important because its properties are connected to the realised structure of the fresh (i.e. hardened) concrete. Degree of filling of the space between the aggregate grains with the cement paste (k_e) is calculated for each concrete mixture as:

$$k_e = \frac{V_{cp}}{V_{s,exp}} \quad (1)$$

where V_{cp} is the cement paste volume, $V_{s,exp}$ is space volume in the aggregate, experimentally measured.

The value of k_e parameter ranged between 0.977 and 2.256. The change of consistence (w) expressed in Vebe seconds depending on the change of parameter k_e is given in the form of the exponential function:

$$w = f(k_e) = a \cdot e^{b \cdot k_e} \quad (2)$$

where *a* and *b* are the numerical coefficients whose value is determined by the statistical data processing. The correlation coefficient values (r^2) were very high, from 0.952 to 0.996. Figure 4 graphically displays the degree of filling of the space between the aggregate grains with the cement paste on the change of consistency for the different granulometric composition and for the different water/cement ratio values (ω_c). For the aggregate "AS" and water/cement ratio ω_c = 0.46 – 0.52, the fresh concrete mixture will be in the stiff consistency zone (classes V1-V2) for all the values k_e < 1.1.

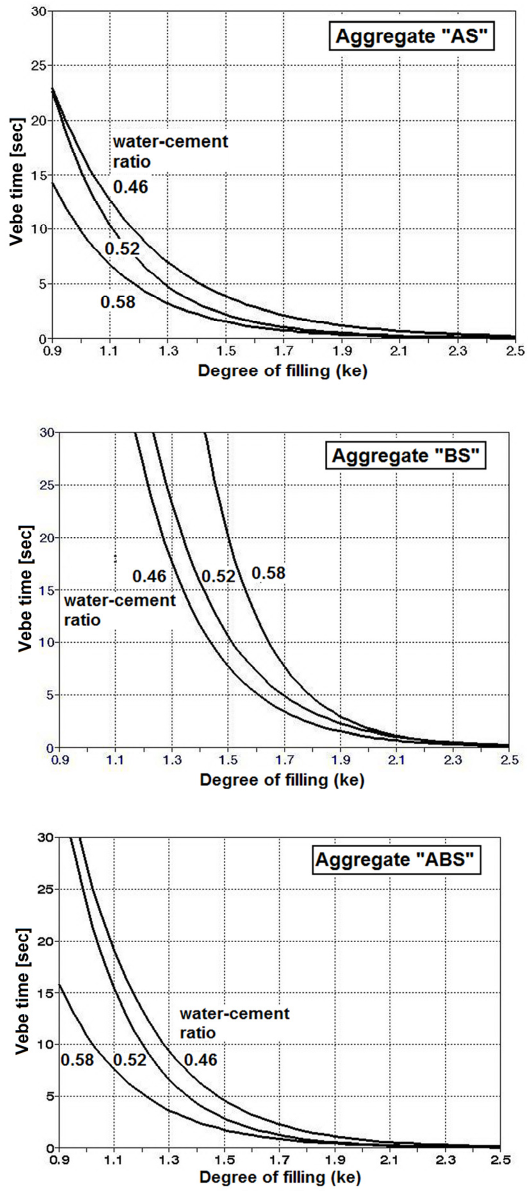

*Fig. 4 – Vebe time as function of k_e parameter for different aggregate particle size distributions and water-*cement ratios (ω_c) *from* 0.46 to 0.58/ *Timpul de remodelare Vebe în funcție de parametrul k_e pentru diferite tipuri de granulozitate a agregatului şi rapoarte apă/ciment (ω_c) de la 0,46 la 0,58.*

The V3 consistency class concrete can be obtained if the value of k_e = 1.0 ÷ 1.1 but only with the increase of the water/cement ratio increase of 0.52 to 0.58. The concrete mixtures made with water/cement ratio ω_c = 0.46 – 0.52 will assume V2-V3 consistency class as the k_e value increases from 1.1 to 1.3 i.e.1.5. At the same time, the concrete mixtures with ω_c = 0.52 ÷ 0.58 and with k_e = 1.3 ÷ 1.5 have V4 class consistency. Further increase of the degree of filling of the space between the aggregate grains with the cement paste (k_e > 1,5) progressively reduces the influence of the particle size distribution of aggregate on consistency. In this event, for all the values of ω_c = 0.46 ÷ 0.58 concrete has V4 consistency class (fluid consistency). If one should, under the previously quoted conditions, define the most favourable area of coefficient k_e values, from the consistency point of view, then those would be the values ranging from 1.2 to 1.4.

If under all these same conditions only the granulometric composition is changed by using the "ABS" type aggregate then the more important difference in type of consistency will be expressed, mostly when the values of ω_c = 0.46 ÷ 0.52. The optimum values of coefficient k_e are now slightly moved upwards and range from 1.3 to 1.5. It can be concluded that the influence of the change of the degree of filling of space in the aggregate with the cement paste on the change of consistency, is not significantly different when the granulometric compositions whose curves are between "AS" and "ABS" are used for making of concrete. On the other hand, dependency of consistency on the degree of filling of the space with cement paste is significantly different when the concrete mixtures are made with “BS” type aggregate which has almost 50% of fine aggregate in its composition, and so the highest grain surface. It can be concluded that the change of granulometric composition from "ABS" towards "BS", i.e. the increase of fine aggregate participation in the mixture, progressively more cement paste is needed to preserve the required consistency, provided that all the other conditions remain the same. The "BS" aggregate has smallest percentage of space between grains, i.e. best grain packing, but, at the same time have the highest grain surface and most prominent grain dry friction which finally results in biggest amount of paste for grain enfolding and reduction of friction in fresh concrete mass. That is why the optimum values of k_e coefficient, from the point of view of fresh and hardened concrete, are the highest in the case of "BS" aggregate usage and range from 1.6 to 1.8.

3.2. The influence of the degree of filling of the space between the aggregate grains with the cement paste on concrete strength

Dependence of concrete compressive strength at 28 days of age ($f_{pc,28}$) on the parameter (k_e) is found in the form of the third degree polynomial function:

$$f_{pc,28} = f(k_e) = a + b \cdot k_e + c \cdot k_e^2 + d \cdot k_e^3 \qquad (3)$$

with the correlation coefficient values r^2 from 0.901 to 0.996. Graphical display of compressive strength change versus the parameter k_e change is given in figure 5.

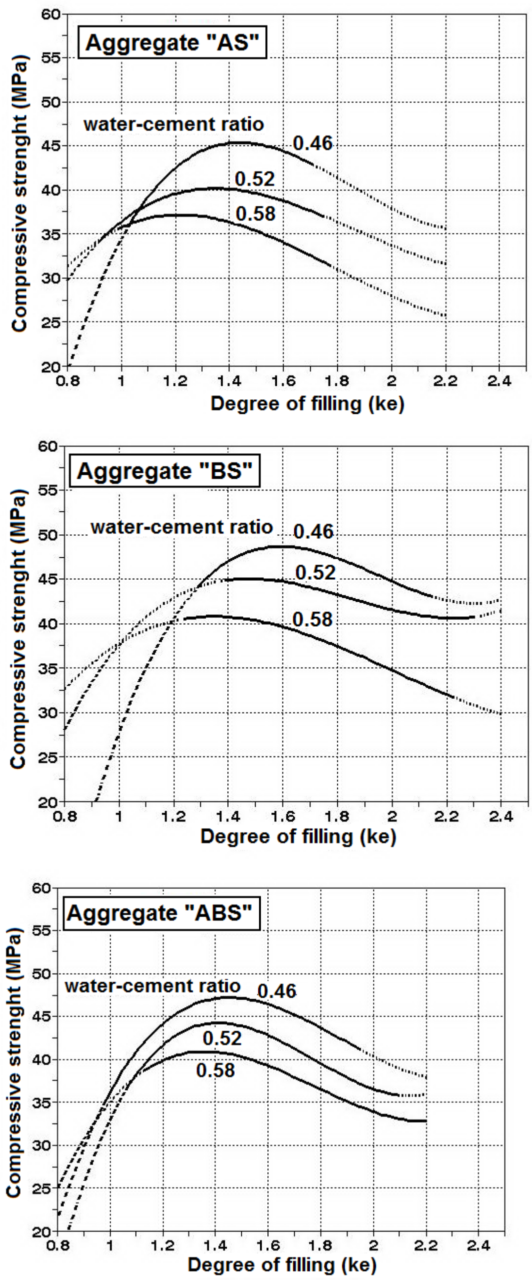

Fig.5 *– The compressive strength as function of k_e parameter, at constant particle size distribution of aggregate and water-cement ratios (ω_c) from 0.46 to 0.58 / Rezistența la compresiune în funcție de parametrul k_e pentru granulozitatea agregatului menținută constantă şi rapoarte apă/ciment (ω_c) de la 0,46 la 0,58.*

The chart $f_{pc,28} = f(k_e)$ has parabolic shape with clearly outlined maximum which corresponds to the maximum strength value achieved at the optimum k_e value. With the increase of water/cement ratio value the k_e parameter value, at which the maximum compression strength values are achieved, decreases. If the aggregate “AS” concrete is taken in the consideration, with water/cement ratio 0.46 the optimum value of k_e is 1.4 ÷ 1.5 where the $f_{pc,max} \approx 46$ MPa. The highest value of the bulk density of some 2410 kg/m^3 corresponds to this "k_e" value while the consistency is 5 – 7 Vebe seconds.

The increase of the water/cement ratio, provided that other conditions remain unchanged, changes the quality of the cement paste. The increase causes the reduction of the optimum value of parameter "k_e", but, simultaneously the reduction of maximum compressive strength value. So, when the water/cement ratio value is 0.52 the maximum strength is achieved when k_e = 1.2 ÷ 1.3 and it is $f_{pb,max} \approx 40$ MPa, which is 13% less than the previous value. Also the bulk density of such fresh concrete is lower, and is around 2400 kg/m^3. The concrete consistency remains unchanged (5 ÷ 7 Vebe seconds). The further increase of the water/cement ratio makes this tendency even more prominent. When the water/cement ratio is 0.58 the optimum value k_e is 1.1 to 1.2, which is lower than in the previous cases. The maximum compressive strength is also lower and amounts to 37 MPa which is a 7,5% reduction in relation to the case when $\omega_c = 0.52$, i.e. 19.5% when $\omega_c = 0.46$. The concrete consistency remains unchanged and has Vebe time of 5 ÷ 7 seconds.

If one observes the area of the co-ordinated system where the values of the degree of filling the space between the aggregate grains with the cement paste are lower than the previously quoted optimum values, a rather abrupt reduction of compressive strength is perceived. The abrupt tendency of strength reduction is more prominent at concrete made with lower water/cement ratio than at those with higher values, due to the rigidity of the fresh concrete mixture and inability to compact it correctly during the installation. This is the zone where the concrete has structure 3 where, as it was pointed out, the characteristics of the aggregate and its granulometric composition have a dominant influence on the characteristics of the concrete [12-14]. The influence of the grain size distribution is so much the higher as the "k_e" values are lower. The friction in the concrete due tot he immediate contact of the aggregate grains is significant and when the "k_e" values become lower than 0.9 the installing and compacting of the concrete become practically impossible, due to the prominent rigid consistency.

When k_e has a higher value than the quoted optimum values, the concrete structure changes gradually from structure 2 into structure 1 (figure 1) followed by reduction of compressive strength. The curves showing the dependence $f_{pc,28} = f(k_e)$ in the area maintain almost equal mutual distance. It is because the concrete strength progressively depends on the quality and quantity of the cement paste. That is why the strength reduction at high k_e values goes as low as the level of the cement paste strength which depends on the level of the cement ratio. According to the course of diagram on the figure 5, a “break” is expected at the value of $k_e \approx 2.2$ after which the further increase of the degree of filling of the space between the aggregate grains effects no significant strength change. It is interesting to point out that for the value of k_e = 1 ("dense" concrete), the compressive strength of concrete made with “AS" aggregate and water/cement ratio from 0.46 to 0.58 is almost constant and amounts to 36 MPa.

4. Conclusions

The influence of the degree of filling of the space between the aggregate grains with the cement paste on the type of concrete consistency should be observed in the light of the realised structure of concrete, taking into account as well the particle size distribution and water/cement ratio. Generally, with the increase of the degree of filling of the space between the aggregate grains with paste (k_e factor) from 0.9 to 2.5 the concrete consistency changes from very high to very low. The increase of water/cement ratio at the constant value of factor k_e causes the higher consistency. At the constant values of water/cement ratio and k_e factor, the higher consistencies are achieved with the particle size distribution in the area of "AS" → "ABS" i.e. when the quantity of small fractions in the aggregate is lower. The increase of the small fractions presence, i.e. when they are in the area of "ABS" → "BS" causes the reduction of the fresh concrete mixture plasticity.

For the granulometric composition "AS" and water/cement ratio from 0.46 to 0.58, from the aspect of fresh and hardened concrete characteristics, the most favourable area of k_e factor value is from 1.2 to 1.4 (structure 2); for the particle size distribution "ABS" that area is from 1.3 to 1.5, while for the particle size distribution "BS" the optimum area is from 1.6 to 1.8.The maximum values of compressive strength are realised when the degree of filling of the space between the aggregate grains (k_e factor) is within relatively narrow range that can be considered optimal. This range depends on the water/cement factor and particle size distribution.

The increase of the water/cement ratio, for the same particle size distribution, reduces the range of the optimum values of k_e. Simultaneously, the value of maximum compressive strength achievable under the given conditions is reduced.

Mark that in this event the concrete consistency does not change. Concrete has structure 2 in the "k_e" factor optimum values zone which ranges between cca. 1.2 and 1.4.

In the area of "k_e" values lower than optimum changes of strength in function of change of the degree of filling of the space between the aggregate grains with paste is abrupt and has almost a rectilinear course, which points to the high sensitivity of this interdependence. The structure of concrete in this zone corresponds to the structure 3.

The area where the "k_e" value is higher than the optimum concrete structure corresponds to the type 1. The change of structure is followed by the reduction of the strength to a certain degree. The compressive strength of concrete depends on the quality and quantity of the cement paste so in the part of the co-ordinated system where the curves show this dependence, they remain equidistant.

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