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Mechanical properties of two-stage concrete modified by silica fume

H.S. Abdelgader[a], R.S. Fediuk[b]*, M. Kurpinska[a], J. Khatib[c], G. Murali[d], A.V. Baranov[b], R.A. Timokhin[b]
[a] Gdańsk University of Technology, Gdańsk, Poland
[b] Far Eastern Federal University, Vladivostok, Russia
[c] Beirut Arab University, Beirut, Lebanon
[d] SASTRA Deemed To Be University, Thanjavur, India
** E-mail: roman44@yandex.ru*

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Abstract. Two-stage concretes, despite the fact that they have proven themselves in various types of construction, have not been studied to the same extent as traditional heavy concretes. Therefore, the article developed the composition of frame concrete with various additives in the composition of the cement-sand mortar. A comparison of the mechanical characteristics of the developed compositions with the addition of silica fume (SF) and superplasticizer (SP) in various combinations. In addition, test specimens were prepared with combinations of water/cement ratios of 0.45, 0.55, and 0.85, and cement/sand ratios of 0.5, 1, and 1.5. A total of 36 mixtures were prepared, silica fume was introduced as a partial replacement of cement in the amount of 6 wt.%. And a superplasticizer equal to 1.2 % of the cement content was added to the water. Compressive strength tests on two-stage concrete cylinders were carried out in accordance with ASTM-C873 and ASTM-C943. Tensile strength was also tested on 3 samples of each composition in accordance with the procedure described in ASTM-C496/C496M. As a result, the development of the strength of two-stage concrete for 7, 28 and 120 days was studied. It was found that the overall compressive strength of the two-stage concrete based on SF, SP and SF + SP was higher than in concrete without any additives. At the same time, the modified concrete has higher strength properties, because it provides better contact due to expansion, as well as by reducing the water-cement ratio in grout. The results obtained allow to design a cement-sand mortar capable of filling all the voids between the coarse aggregate, thereby creating a dense structure of two-stage concrete.

1. Introduction

Concretes obtained from high-tech self-compacting concrete mixtures based on modern superplasticizers, along with a number of technological advantages, in terms of structural properties, have a number of disadvantages due to the increased concentration of the mortar component, which leads to decrease in the initial modulus of elasticity [1], increased shrinkage [2] and creep [3]. To improve deformation indicators of concrete quality, it needs minimizing the capacity of the mortar component, which ideally should be equal to the volume of coarse aggregate voids [4].

Two-stage concretes (TSC) of the frame structure are produced according to separate technology by injecting a low-viscosity mortar component into the voids between of coarse aggregates, fixed in volume, or by immersion in the low-viscous mortar component of coarse aggregate. This casting method is beneficial in construction work, where there are difficult concreting conditions and limited access to the site [5–7]. It is widely used in various construction applications, for example, concrete for restoration works, hydraulic structures and massive concrete structures [8–17]. TSC's special concreting technology leads to several

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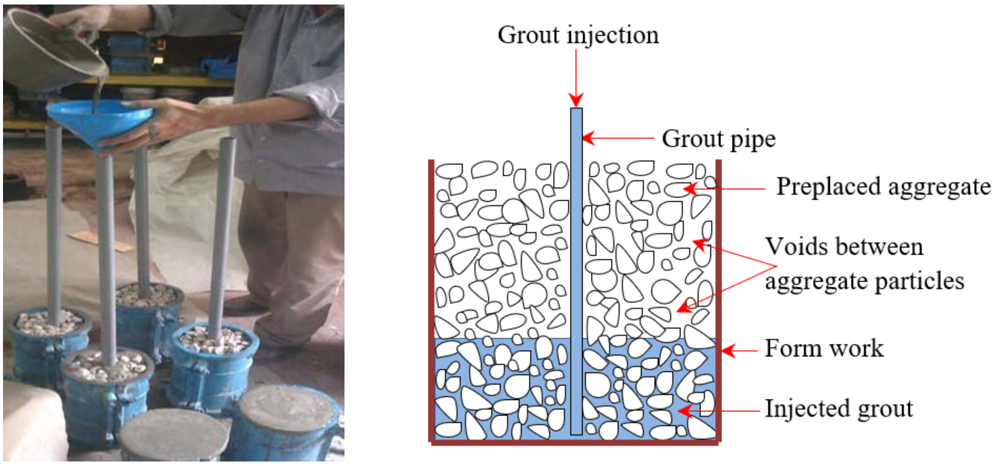
advantages [18–23]. Recycled concrete aggregates, which usually cause poor performance and serious problems with pumping due to their higher water absorption, will not contribute to problems with concreting in TSC technology [24, 25]. Production of two-stage concrete has a fairly simple technology, because the same raw materials are used as for conventional concrete: cement, crushed stone, fine-grained aggregate, water, and the necessary modifiers. Differences are only at the production stage. First, the wet cleaned coarse aggregate is accommodated into a timbering in place. Then a specially grout is injected into a timbering from below by pressure of injection and gravitation to fill all the voids, cementing the units to the monolith, as shown in Figure 1. When grout goes up via aggregates, all air and water are discharged. As a result, a dense material is obtained with reduced porosity. Thanks to this simple technology, concrete is maximally compacted without the use of additional equipment [26–30]. Various additives can be selected as needed to improve strength, adhesion and physico-mechanical properties [31–37]. The main difference in materials compared to conventional concrete is that only fine sand (less than 2 mm fraction) and coarse aggregate (usually more than 20 mm) are used as aggregates, which eliminates the need for expensive gravel materials. Nonstandardly a lot of rubble in TSC (up to 70 %) in combination with the use of sand, leads to minimization of the cement component, respectively, reduces total shrinkage and increases efficiency compared to conventional concrete [38–43]. TSC cement mix must be manufactured with high workability so that grout can spread through coarse aggregates. However, due to the uniqueness of the preparation technology of two-stage concrete, it is necessary to modify a grout by various additives. Unfortunately, information in this regard is currently very limited.



(a) (b)

Figure 1. Casting a two-stage concrete: (a) making the samples; (b) scheme of pumping a grout through a pipe.

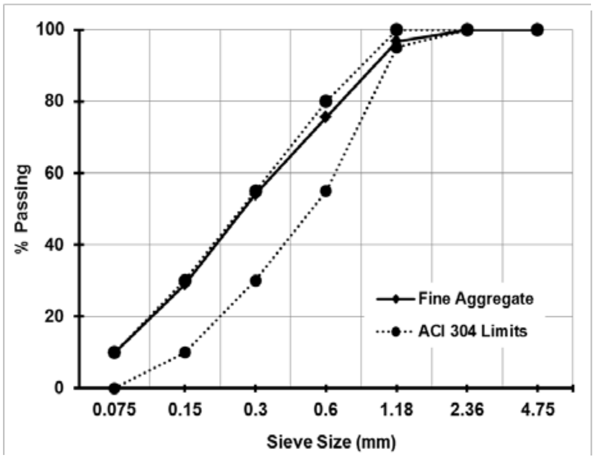
In particular, Coo and Pheeraphan [44] studied the use of fly ash and limestone as cement grout fillers. The effect of some active additives on a grout investigated by Nesvetaev [46]. Abdelgader [1] and Najjar [40] investigated the effect of superplasticizers on the properties of cement grout. At the same time, it is known that silica fume and superplasticizer have well reputation for established in more studied types of concrete.

So, the aim of the paper was to study the effect of silica fume and superplasticizer additives in various combinations to strength properties of two-stage concrete.

2. *Materials and methods*

2.1. *Materials*

The two main components in the manufacture of two-stage concretes are coarse aggregate and grout [22, 48]. Accordingly, the selection of coarse aggregates is of paramount importance. In the study, crushed dolomitic limestone with a maximum size of 37.5 mm, a specific gravity of 2.68, a crush strength value of 18.83 %, an abrasion value of 23.81 %, and an absorption value of 1.66 % was used as a «frame» of concrete. Both coarse aggregate and fine aggregate evaluation is crucial in terms of the workability of grout. Natural quartz sand with a specific weight of 2.68 and a maximum size of 2 mm was used in the production of cement grout. The particle sizes of small and coarse aggregates used in this study are shown in Figure 2 [20, 27]. Ordinary Portland cement (OPC) CEM I 42.5 N (Libyan Cement Company) was used for manufacturing of grout (Table 1). In the study, two types of additives were used: superplasticizer (SP) and silica fume (SF). The SP used was ViscoCrete-10 (Sika, Switzerland) and it was applied at a measuring of 1.2 % (by weight of OPC). Silica fume powder, containing 95 % SiO_2 (specific surface area of 20,000 m^2/kg), was the only mineral additive applied. SF was used in dried form as an additive in the amount of 6 % (by OPC wt.).



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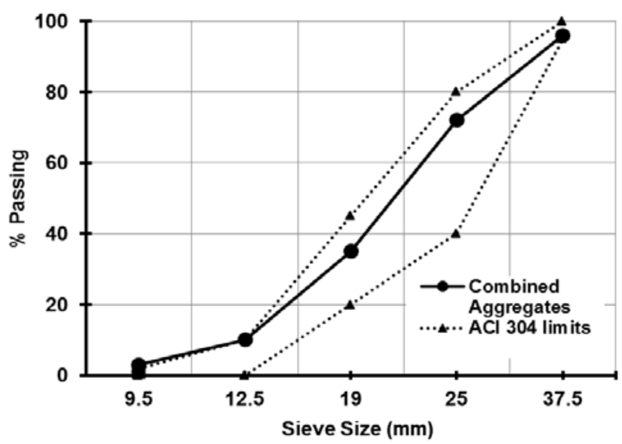


b)

Figure 2. Particle sizes of fine (a) and combined (b) aggregates.

Table 1. Chemical analysis of OPC and SF.

Component	OPC (%)	SF (%)
SiO_2	21.22	95.30
Al_2O_3	4.45	0.17
Fe_2O_3	4.08	0.08
CaO	62.98	0.49
SO_3	1.98	0.24
Na_2O	0.33	0.19
L.O.I	0.67	4.7

2.2. Grout Mix Preparation

Cement-based groutings are a mixture of cement, water, silica-containing component, superplasticizer, and fine aggregate. Constancy of properties, which is the adhesion of a liquid solution and it no delamination, is a significant characteristic for liquid grouting of coarse aggregates. If the grout is prone to delamination, it cannot be guaranteed uniform when filling a formwork. When segregation and water separation occur after pouring the cement mix, the connection with a «frame» may be broken. The main characteristic, on which the strength properties depend, as well as the rate of water separation and plasticity, is the water/cement ratio (w/c). Here, the principle of designing traditional concrete, which states that with a decrease in w/c, the complex of strength characteristics (compression, adhesion, tensile) of a grout obtained is raised. However, at lower ratios of water and cement, the grout loses its fluidity, which means that the mixture has become too thick because cannot seep between of coarse aggregate particles. Although the cement/sand ratio does not significantly affect the strength properties of cement mixture or TSC manufactured, it does have a significant effect on flowability, air removal speed and mixture constancy. Silica fume affects the characteristics of the grout by different itineraries. This is a very pozzolanic material with high reaction potential. Consequently, addition of a silica-containing component into the composition of the binder leads to a change in the rheological properties of the grout, and, then, in the mechanical properties of the cured composite. As a rule, mixtures with SF are more binded and have raised need for mixing by water. Therefore, using of superplasticizers is necessary to maintain the workability of the grout [35, 49–50]. Fine aggregate (i.e. sand) is a significant unit in the rheological planning of grout. Ideally, fine sand without gaps in its gradation is preferred. When using sand with coarse particles larger than 3 mm, the segregation risk of is higher than with smaller sand, where constancy can be supported with reduced water content [27, 51].

The choice of the $w/c/s$ ratio is extremely important in two-stage concrete, since the amount of water and sand controls the pumpability and distribution of the mixture [9, 27]. The absolute volume method was applied for the study to make proportions of self-compacting grout mixes, followed by adjusting the components of the mixture to characterize mixtures by filling, throughput, and segregation resistance [1]. The voids content between the coarse aggregates was nearly 50 %, and it bulk density was 1,430 kg/m^3. In total, the study used 36 mixtures, apportioned in 4 series. Each group consisted of a combination of 9 mixtures with permanent indicators: w/c — 0.45, 0.55, and 0.85 and c/s — 0.5, 1, and 1.5. The 1st series was developed with additives free and was designated in the paper as (no additives). SP was applied only for the 2nd series at constant content of 1.2 % by OPC wt. SF was used only in the third group as a mineral additive at a dosage of 6 % by weight of cement. The combination of both SF and SP was used in the fourth group with the same dosages as in the other groups, and is referred to in the text as (SP + SF), the mixing code in the table is also used. Grout was prepared by mixing the starting components by an electric mixer for about two minutes in a dry form, followed by three minutes stirring with water to make the required homogeneity substance. Table 2 lists the proportions of everything tested two-stage concrete mixtures.

Table 2. Tested mixes ratios.

Mix ID	Water/Cement ratio	Cement /Sand ratio	Quantity (kg/m^3)			
			Cement	Silica Fume	Water	Sand
1		1/0.5	524	31.4	236	262
2	0.45	1/1	438	26.3	198	438
3		1/1.5	377	22.6	170	565
4		1/0.5	474	28.5	261	237
5	0.55	1/1	403	24.2	222	403
6		1/1.5	350	21.	193	526
7		1/0.5	369	22.2	314	185
8	0.85	1/1	325	19.5	276	325
9		1/1.5	290	17.4	246	434

2.3. Manufacturing and testing of samples

During the production of two-stage concrete, the grouting of aggregates can be carried out either by gravity or by pumping a grout at the base of the formwork so that it can move up through the voids between the parts of the aggregates. The grout components were weighed separately before mixing. Mixing components is performed in a dry form. This is due to the fact that SF, if it is added to the wet mixture, begins to accumulate in certain places, forming miniature feeble balls. The cement-sand mixture was shifted out the mixer into the cylinder sample with a size of 150×300 mm using a pipe diameter of 20 mm and a length of 1.5 m using a funnel. The pipe was placed in the center of the cylinder before adding a large aggregate in order to most accurately model an authentic manufacturing technology. When the grout rises through crushed stone, only its end remained below the grout. All samples were cured until the day of testing in water at 20°C. A series of tests for compressive and tensile strengths was performed for different mixes, cured during 7, 28 and 120 days (3 samples for each test). Tests on compressive strength on TSC cylinders were made in accordance with ASTM-C873 [52] and ASTM-C943 [53]. Tensile strength was also tested on 3 samples of each composition according to the procedure described in ASTM-C496/C496M [54].

3. Results and Discussion

3.1 Characteristics of Grout

Figure 3 shows a microstructure of new growths of OPC and SF.

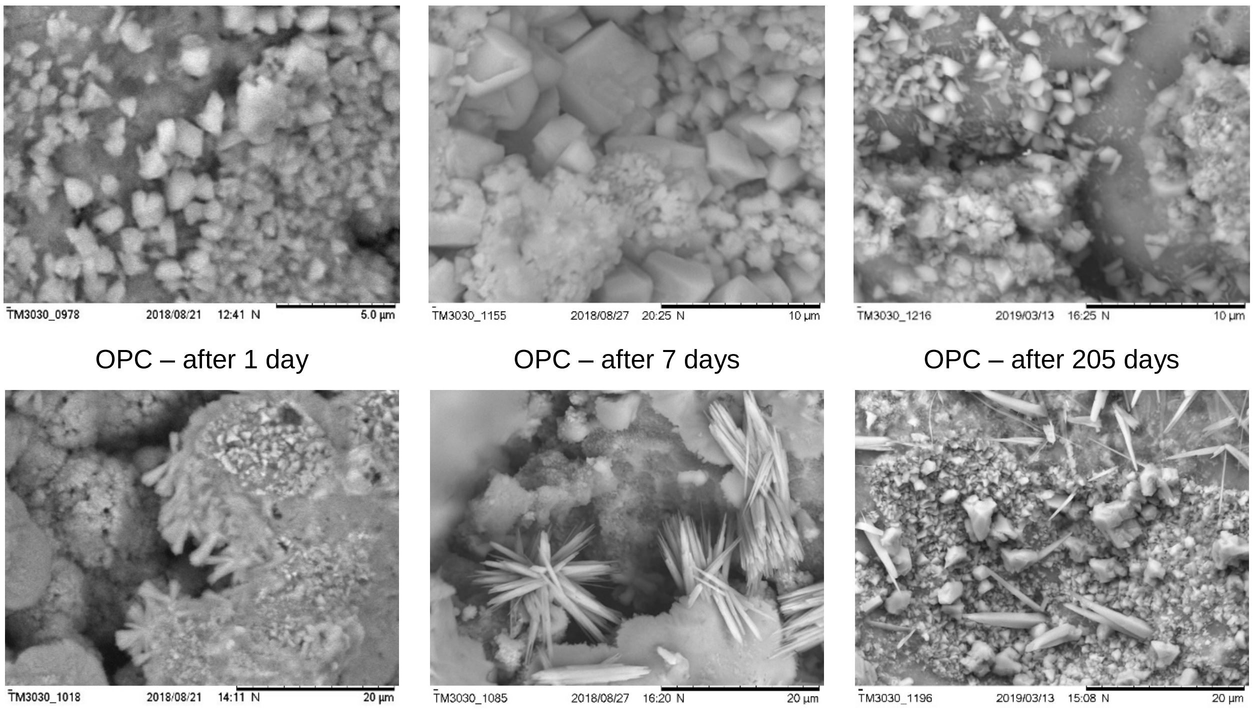


Figure 3. Microstructure of new growths in cement stone with OPC and SF.

The grout must have basic properties such as flow characteristics (consistency of the mortar) and sedimentation, which is suitable for use in two-stage concrete. It was investigated that raising *w/s* at permanent *c/s* content leads to an increase in fluidity. Increasing the amount of water reduces the mixture's cohesion and internal shear forces, which allows the grout to pass by and above each other loosely. At superior ratios of cement and sand, the internal flowability of the mortar is likely to be due to the higher ratio of superplasticizer to sand. The fluidity of cement-sand mixtures with excellent *w/c* ratios may increase due to the low stability in these mixtures. During mixing in the laboratory, it was observed that in mixes with a higher ratio of water to cement, fine aggregate grains drown almost at once since ceasing the blender. This may indicate potential problems with this particle size of fine aggregates for two-stage concretes. The cement-sand mixture should be able to move loosely through the large-grained crushed stones so that after they are applied, everything is coated. Naturally, this was complicated at decreased cement/sand ratios (*c/s* = 0.5), as shown in Figure 4, where the grout could not fill all voids. Grout prepared from these composite ratios cannot be used to produce TSC due to the large volume of voids between coarse aggregates, thus potentially weak areas. It was found that large volumes of voids are a problem in only two of the «driest» mixtures; water/cement = 0.42 with cement/sand = 0.5 and water/cement = 0.42 with cement/sand = 1. However, other mixtures have enough flowability to infiltrate into the “frame” of the aggregates.

It was either proved that with a permanent *c/s* ratio, higher in the water leads to a steady increase in the sedimentation speed, while higher *c/s* ratios are liable to a more expressed sedimentation speed. The predominance of smaller particles in the mixture at increased *c/s* ratios, where rateably more binder in volume, reason the formation of gaps in the cement mortar as a whole. To maintain stability, it is recommended that fine grained aggregate and cement material be well sorted. According to the general empirical equations given by Abdelgader [1], sedimentation and fluidity can be calculated.

3.2 Compressive Strength

It has been found that the main rule of conventional concrete, that states that increasing the *w/c* ratio will drive to a decrease in strength properties, is also true for TSC samples. Table 3 lists the compressive strengths for the developed two-stage concretes with different ratios of water/cement, cement/sand and various chemical and mineral impurities. However, the results of compressive strength for the most dense mixtures with *w/c* = 0.42 at *c/s* = 0.5 and *c/s* = 1 were not included in Table 3, due to the fact that in paragraph 3.1 their inefficiency is proved. The previous articles [2, 10] show that the strength of the grout is most tender to modifications in the *w/c* ratio than concrete. This creates meaning in that case it takes into account, how two-stage concrete transfers compression tension. In case if outer energies are attached to the two-stage concrete, the inner large-grained «frame» mainly transfers the load through a dot hookup of particles. When crushed stones are destroyed and deformed, the solution draws it down. It should be assumed that most of the supporting capacitance in concrete is provided afore the onset of cracking in coarse aggregates, which may explain why a significantly more durable solution does not allow one to obtain concrete of proportional strength. The results showed in general that TSC mixtures showed a similar strength properties tendency with regard to the style of additives. As a rule, at the same age and proportions, it was observed that an increase in the heat transfer coefficient slightly decreases the strength properties of the two-stage concrete, that is apparently associated with a decrease in the fluidity and permeability of the solution, which leads to the formation of a two-stage concrete microstructure with a cellular internal structure with local fastening of the aggregates «frame». The use of superplasticizer improves fluidity and permeability of solution and drives to improved strength properties. In addition, using of only silica fume, or it together with superplasticizer showed desirable results in strength properties by comparison to mixtures with no additives as well as only with superplasticizer, and this fact can be explained by the because:

a) higher flowability of the solution is with using superplasticizer, which allows cement mortar fill entirely hollows among crushed stones;

b) pozzolanic reactivity of the silica fume leads speed-up of the hydration, which, thereafter, cause to an increase in the package solidity of the particles of concrete microstructure. For instance, when the cement/sand relation is 1: 0.5, the use of a combination of SF and SP leads to growth of strength after 28 days of curing on a par of 40 % for all the considered water/cement relations. Contrariwise, growth a cement/sand value for the similar *w/c* value results in middle decline of strength properties of 12 % at the age of 28 days, this is not an important result.

Other significant result which apparent in Table 3, is the lower compressive strength of the TSC. This decrease is due to water separation and a lower connection among the cement-sand mixture and crushed stones inside of sample. However, the level of strength characteristics will bond on the aptness of the grout to oppose to water separation [8, 55, 56]. The sediment of mix components usually takes place on the bottom of the crushed stones, which leads to the creation of hollows. These hollows form feeble transition areas of aggregate and grout in TSC, preventing the solution from binding to coarse aggregates [29, 32]. In addition, TSC blends, both without impurities and with SF, create hollows (great capillary pores), that are roots of feebleness in concrete. Figure 5 shows image obtained using a scanning electron microscope (SEM) illustrating a TSC sample. These hollows were created as a result of the surplus water which stayed as spare water in the grout of the two-stage concrete. The capacity of capillary pores rised depends on growth spare water and relies on the grade of hydration of the binder. Conversely, a TSC blend with less spare water formed fewer hollows than another two-stage concrete blends, so reach a better strength properties of two-stage concrete.

Table 3. Average Compressive Strength Outcomes of two-stage concretes.

w/c	Additives	Curing Time (days)			Curing Time (days)			Curing Time (days)		
		7	28	120	7	28	120	7	28	120
		c/s = 1: 0.5 (MPa)			c/s = 1:1 (MPa)			c/s = 1:1.5 (MPa)		
0.45	SF	16.79	18.49	26.59	16.60	17.35	25.65	13.58	16.22	25.09
	SP	12.07	18.67	20.18	13.00	17.35	19.05	15.40	15.47	17.17
	SF+SP	17.35	25.65	28.29	16.79	22.63	26.03	13.95	22.26	25.65
	No additives	11.13	15.28	20.37	11.13	14.15	18.11	9.24	13.00	16.03
0.55	SF	13.29	15.85	24.89	11.88	15.10	20.56	10.75	13.58	19.81
	SP	14.34	16.79	20.75	12.64	16.03	20.56	11.32	14.52	18.49
	SF+SP	13.20	21.32	26.88	12.83	19.24	21.50	11.70	15.00	21.87
	No additives	8.67	12.45	15.85	8.49	9.05	13.58	7.73	8.49	12.07
0.85	SF	7.36	10.56	13.58	5.28	9.43	12.07	4.90	9.43	11.69
	SP	6.98	13.20	16.22	8.11	11.51	15.47	8.86	10.94	14.52
	SF+SP	9.05	14.71	16.98	9.81	11.70	15.85	10.19	11.32	15.47
	No additives	6.60	8.29	11.69	4.53	7.36	10.19	3.96	5.66	9.81

Figure 4. The grout was not able to fill all the voids between coarse aggregates.

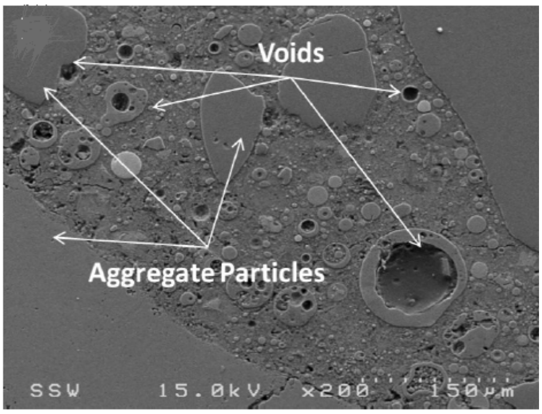


Figure 5. SEM of specimen of TSC.

The results can be described by the proposed formula:

$$f_c' = A + B \times w/c + C \times \left(w/c\right)^D + E \times \left(c/s\right), \qquad (1)$$

here f_c` is the calculated compressive strength of two-stage concrete at 120 day (MPa). Table 4 lists the values of the regression factors.

Table 4. Regression Factors for Equation 1.

Additives	Regression Constants					Correlation coefficients
	A	B	C	D	E	
Silica fume	23.838	–19.641	7.022	–0.815	–2.715	0.975
Superplasticizer	–110.44	–172.456	291.909	0.418	–3.823	0.947
Silica fume + Superplasticizer	8.73	7.265	2.399	–2.456	–2.395	0.977
No additives	7.34	5.278	1.427	–2.647	–3.357	0.979

The correlation coefficients close to 1 confirm the reliability of the results obtained for all the compositions developed.

3.3 Tensile Strength

Splitting tensile strength is generally applied for appreciate one of important TSC property. Table 5 lists the results of the TSC tensile experiment for various mixes. It was found that the tensile strength of a two-stage concrete becomes higher with decreasing c/s. A decrease in the water/cement value below 0.42 resulted in the appearance of a cellular structure, which partially binds coarse aggregates, which leads to a decrease in tensile strength. Tensile strength at splitting after 7 days was poor, notably for no additive mixes, but furthers its progress speed growth over time. For example, tensile strength at 7 days for a mixture that does not contain additives was 20 % worse than that of a mixture with silica fume and superplasticizer additives. As a rule, the higher the compressive strength of the TSC, a higher the tensile strength of the TSC, this is consistent with previous studies [1, 9, 13, 17]. In addition, better mechanical adhesion between particles lead to higher tensile strength in TSC.

Table 5. Average Tensile Strength Outcomes of two-stage concrete.

w/c	Additives	Curing Time (days)			Curing Time (days)			Curing Time (days)		
		7	28	120	7	28	120	7	28	120
		c/s = 1: 0.5 (MPa)			c/s = 1:1 (MPa)			c/s = 1:1.5 (MPa)		
0.45	SF	2.075	2.428	2.785	1.933	2.357	2.738	1.789	1.982	2.547
	SP	1.873	2.405	2.783	1.655	1.950	2.542	1.137	1.693	2.167
	SF+SP	2.452	2.972	3.772	1.982	2.765	2.207	1.796	2.363	3.111
	No additives	1.745	1.837	2.547	1.604	1.673	2.406	1.507	1.603	1.984
0.55	SF	1.620	1.626	2.359	1.677	1.653	2.078	1.430	1.510	1.698
	SP	1.666	2.213	2.266	1.636	2.071	2.165	1.415	1.688	2.075
	SF+SP	1.716	2.122	2.265	1.691	1.839	2.170	1.603	1.608	2.124
	No additives	1.424	1.522	1.768	1.383	1.518	1.628	1.180	1.190	1.579
0.85	SF	1.226	1.508	1.603	1.037	1.340	1.536	0.713	1.320	1.483
	SP	0.852	1.450	2.452	1.084	1.320	1.549	1.179	1.320	1.601
	SF+SP	0.943	1.674	2.304	1.226	1.406	1.699	0.943	1.264	1.625
	No additives	0.884	1.461	1.529	0.870	1.320	1.622	0.578	1.226	1.447

3.4 The ratio of strengths of compressive and tensile

The outcomes of this research represent that there is a nice depend among both strengths. When a compressive strength increases, a tensile strength is growth in a similar way. In this paper the Equation 2, was created using regression analysis to relate the tensile strength at 120 days (f_t) to compressive strength at 120 days (f_c`).

$$f_t = a + b \times f_c' + c \times \left(f_c' \right)^d . \quad (2)$$

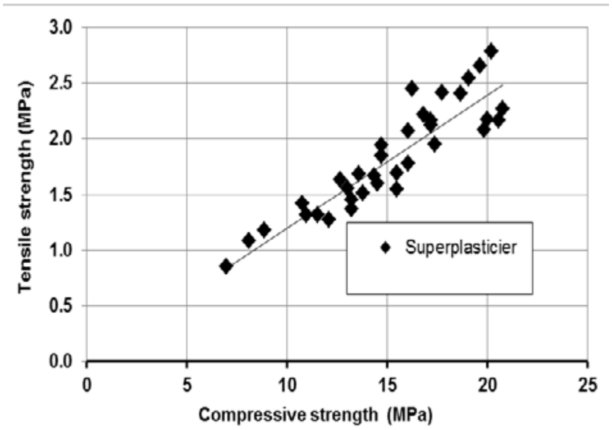


Figure 6. Dependence among compressive strength and tensile strength for created mixes.

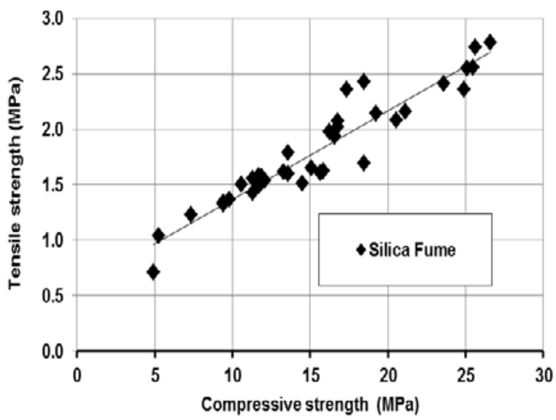


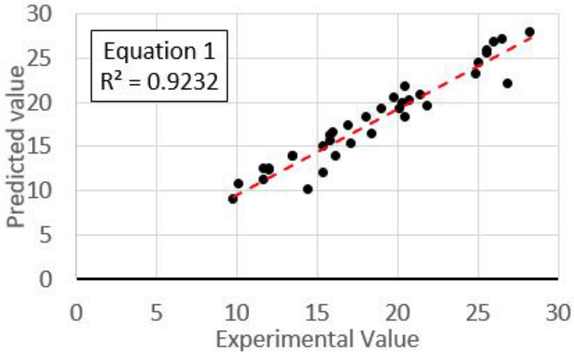
Figure 7 shows the graphical presentation of this relationship.

Table 6 shows the values of the regression factors.

Table 6. Regression Coefficients for Equation 2.

Additives	Regression constants a	b	c	d	Correlation Factors
SF	–6.048	0.223	26.158	–0.674	0.943
SP	–78.020	–0.003	75.050	0.022	0.901
SF+SP	66.074	0.584	–52.448	0.122	0.907
No additives	–4.197	0.249	24.023	–0.871	0.936

Compressive and tensile strengths calculated by equations 1 and 2, respectively, are shown in Figure 7. Compressive strength has a smaller deviation between the experimental value and the predicted ones, and R^2 reaches 0.9, which shows the accuracy of equation 1. In the case of tensile strength, obtained from Equation 2, the deflection among the empirical and predicted values is significantly less when the value of R^2 is 0.6436. Many points fall off the line, indicating the need for more tests and data.



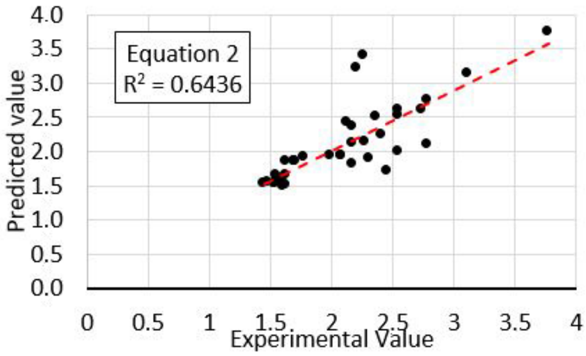


Figure 7. Comparison of experimental values with predicted ones.

3.5. Strength properties of partially bound concrete

The strength results for concrete samples obtained with a water/cement value of 0.42 were not presented in the main analysis. At the same time, 2 specimens were tested for compressive strength and tensile strength with 28-day curing, and the results are shown in Table 7. Although the grout did not completely fill the cylindrical specimens, the 28-day strengths showed a fairly high value. This notice also confirms that the coarse aggregate framework is important for both TSC strengths.

Table 7. Compressive and tensile strength of partially bound concrete (w/c =0.42).

Compressive strength at 28 day (MPa)		Tensile strength at 28 day (MPa)	
Specimen	Average	Specimen	Average
21.1 25.3	23.2	2.21 1.32	1.8

4. Conclusion

1. The lower limit of the water-cement ratio of a grout (0.42) is established, upon reaching which dense structure of two-stage concrete cannot be ensured.

2. A formula is proposed for calculating the compressive strength of TSC with various combinations of silica fume and superplasticizer, as well as with various water-cement and cement-sand ratios.

3. Tensile strength of a two-stage concrete becomes higher with decreasing c/s. In addition, better mechanical adhesion between particles leads to higher tensile strength in TSC.

4. Conducting a correlation between compressive strength and tensile strength of the developed concrete, it shows that with an increase in one type of strength, the other also increases. Considering a small amount of work on these concretes in world literature (and the structure differs significantly from traditional heavy concrete), obtaining reliable results (as indicated by almost all coefficients of correlation) is a definite contribution to the study of two-stage concrete.

5. Even with a low water-cement ratio, when the grout did not completely fill the cylindrical specimens, the 28-day strength showed a rather high value. This notice also confirms that the coarse aggregate structure is important for both TSC strengths.

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Contacts:

Hakim Abdelgader, +79502817945; hakimsa@poczta.onet.pl

Roman Fediuk, +79502817945; roman44@yandex.ru

Marzena Kurpinska, +79502817945; marzena.kurpinska@pg.edu.pl

Jamal Khatib, +79502817945; j.khatib@bau.edu.ib

Gunasekaran Murali, +79502817945; murali_220984@yahoo.co.in

Andrey Baranov, +79502817945; de_montgomery@mail.ru

Roman Timokhin, +79502817945; gera210307@yandex.ru

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Физико-механические свойства каркасного бетона, модифицированного кремнеземом

***Х. Абделгадер*[a], *Р.С. Федюк*[b]*, *М. Курпинска*[a], *Д. Хатиб*[c], *Г. Мурали*[d], *А.В. Баранов*[b], *Р.А. Тимохин*[b]**

[a] Гданьский политехнический университет, Гданьск, Польша

[b] Дальневосточный Федеральный Университет, г. Владивосток, Россия

[c] Бейрутский арабский университет, Бейрут, Ливан

[d] Университет САСТРА, Танджавур, Индия

** E-mail: roman44@yandex.ru*

Ключевые слова: каркасный бетон, кремнезем, физико-механические свойства, цемент, крупный заполнитель

Аннотация. Каркасные бетоны, несмотря на то, что хорошо зарекомендовали себя в различных видах строительства, изучены не в такой степени, как традиционные тяжелые бетоны. Поэтому в статье разработаны составы каркасных бетонов с различными добавками в составе цементно-песчаного раствора. Проведено сравнение механических характеристик разработанных композиций с добавлением кремнезема (SF) и суперпластификатора (SP) в различных комбинациях. Кроме того, образцы для испытаний готовили с комбинациями соотношений вода/цемент 0,45, 0,55 и 0,85 и соотношений цемент/песок 0,5, 1 и 1,5. Всего было приготовлено 36 смесей, в качестве частичной замены цемента в количестве 6 мас.% вводили кремнезем, а в воду добавляли суперпластификатор, равный 1,2 % содержания цемента в воде. Испытания прочности на сжатие на двухступенчатых бетонных цилиндрах были проведены в соответствии с ASTM-C873 и ASTM-C943. Прочность на растяжение также тестировали на 3 образцах каждой композиции в соответствии с процедурой, описанной в ASTM-C496/C496M. В результате, было изучено развитие прочности каркасного бетона за 7, 28 и 120 дней. При этом было обнаружено, что общая прочность на сжатие каркасного бетона на основе SF, SP и SF + SP была выше, чем в бетоне без каких-либо добавок. При этом, модифицированный бетон обладает более высокими прочностными свойствами, поскольку обеспечивает лучший контакт за счет расширения, а также за счет снижения водоцементного соотношения в цементном растворе. Полученные результаты позволяют проектировать цементно-песчаный раствор, способный заполнять все пустоты между крупным заполнителем, тем самым, создавая плотную структуру двустадийного бетона.

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Контактные данные:

Хаким Абделгадер, 89502817945; эл. почта: hakimsa@poczta.onet.pl

Роман Сергеевич Федюк, +79502817945; эл. почта: roman44@yandex.ru

Марзена Курпинска, 89502817945; эл. почта: marzena.kurpinska@pg.edu.pl

Джамал Хатиб, 89502817945; эл. почта: j.khatib@bau.edu.ib

Гунасекаран Мурали, 89502817945; эл. почта: murali_220984@yahoo.co.in

Андрей Вячеславович Баранов, 89502817945; эл. почта: de_montgomery@mail.ru

Роман Андреевич Тимохин, +79502817945; эл. почта: gera210307@yandex.ru