doi: 10.5862/MCE.68.8

Self-compacting concrete with limestone powder for transport infrastructure

Самоуплотняющийся бетон с карбонатным наполнителем для объектов транспортной инфраструктуры

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Key words: self-compacting concrete; limestone powder; energy efficiency; strength; buildings; construction; civil engineering; water permeability; frost resistance

Ключевые слова: самоуплотняющийся бетон; карбонатный наполнитель; энергосбережение; гражданское строительство; конструкции; прочность; водонепроницаемость; морозостойкость

Abstract. At the beginning of XXI century in civil engineering and buildings of transport infrastructure, such as tunnels, elements of bridges, viaducts and roads, it is more expedient to use conventionally vibrated concretes which have almost universally replaced prefabricated constructions. However, in objects with high congested reinforcement or in cases where vibration is impossible it is more preferable to apply self-compacting concrete (SSC) mixtures. SCC possesses the ability to take form shape without any mechanical aid. The most important requirement for SCC is high flowability without the segregation of aggregate during placement. Despite the low water-cement ratio of the fresh self-compacting concrete mixture the bleeding is still possible. That is why fillers such as natural pozzolana, calcined clay (metakaolin), silica fume, fly-ash, slag, and quarry dusts should be used. Furthermore, mineral admixtures can improve energy efficiency and particle packing, decrease cost and permeability of self-compacting concrete. In this study, the properties of SCC with limestone powder as partial replacement of Portland cement was established by applying mathematical experiment planning method. The obtained SCC gave high early compressive strength within 3 days in the range of 41.3 MPa while its 28 day strength ranged of 69.0 MPa. The result of this study indicated the possibility of adding limestone powder in SCC with optimum percentage content around 38 %. The researched SCC had density of hardened and fresh concrete mix in the ranges of 2438 kg/m3 and 2452 kg/m3 respectively. The investigated SCC concrete with limestone powder showed high rate of water permeability in the range of 1.6 MPa (W16) and high frost resistance in the ranges of F2400. It can be explained by additive's high water retention capacity and increase of hydration degree and, as a consequence, decrease of capillary porosity. That is why the developed SCC with limestone powder has high compressive strength and excellent durability performance.

Аннотация. На объектах гражданского строительства и транспортной инфраструктуры в конструкциях, имеющих высокий коэффициент армирования, и в случаях, когда вибрирование бетонных смесей осуществить не представляется возможным, необходимо применение эффективных самоуплотняющихся бетонных смесей, которые получили широкое распространение в последние десятилетия в мировой практике. В работе представлены результате экспериментальных исследований при разработке состава самоуплотняющегося бетона для объектов транспортной инфраструктуры с использованием наполнителей на основе отходов дробления карбонатных пород. Для оптимизации состава применялся трехфакторный метод математического планирования эксперимента, композиционный план на кубе типа В3, обеспечивающий максимальную прочность при достижении требуемых технологических показателей. Установлено, что введение эффективного разжижжителя в виде гиперпластификатора, значительно снижает водосодержание бетонной смеси, что предотвращает расслаиваемость самоуплотняющегося бетона и повышает эксплуатационные свойства: прочность, морозостойкость, водонепроницаемость. Экспериментально установлено, что увеличение содержания карбонатного наполнителя ведёт к повышению прочности только до определённого предела, оптимальная дозировка которого, соответствующая максимальной

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прочности, составляет 0.38 от массы цемента. Карбонатный микронаполнитель, обладая высокой водоудерживающей способностью, повышает степень гидратации цемента, способствует уменьшению капиллярной и общей пористости, тем самым влияя на показатели прочности. Получен самоуплотняющийся бетон со средней плотностью 2438 кг/м3, прочностью на сжатие 69 МПа, морозостойкостью F2400 и водонепроницаемостью W16.

Introduction

At the beginning of XXI century in constructions, such as tunnels, elements of bridges, viaducts and roads conventionally vibrated concretes are widely used. However, it is more preferable to apply self-compacting concrete mixtures in structures with high density reinforcement or in cases where vibration is impossible [1]. Due to high rate of flowability self-compacting concrete takes form shape and passes through the bars without any vibration. Self-compacting concrete has several advantages such as technological benefits, environmental impact and energy efficiency [2].

The difference in concrete mix design between SCC and conventionally vibrated concrete is in lower coarse aggregate content, increased paste content, low water/powder ratio, increased superplasticiser [3]. The required level of flowability (slump more than 600 mm) can be achieved by adding polycarboxylate-based admixtures with maintaining of technological properties such as workability retention at the period of setting time into the formwork [4, 5]. Despite low water-cement ratio bleeding of the mix is still possible.

The high cost of SCC resulted from the high cement content is the main factor impeding the widespread of SCC use. Since cement is the most expensive component of concrete, its reducing content is an economical solution. The cost of SCC can be decreased incorporating various supplementary cementitious materials such as natural pozzolana [6], calcined clay (metakaolin) [7], silica fume, fly-ash [8], slag [9] and quarry dusts [10]. The mineral admixtures can improve particle packing and decrease the permeability of concrete. Therefore, the durability of concrete is also increased.

Besides the economical benefits, the use of recycled waste materials in concrete could reduce environmental pollution and carbon dioxide emission. Large volumes of these powders are accumulated and it is a big problem to propose utilization of these by-products from the aspects of disposal and health hazards [11].

In addition supplementary cementitious materials do not only decrease the cost of self-compacting concrete [12], but also improve flowability [13] and durability [14], reduce the heat of hydration in massive structures [15], increase early strength and control bleeding [16].

Calcium carbonate based mineral fillers are widely used and can give excellent rheological properties and a good finish. Limestone powder is a by-product collected from the quarrying process of carbonate rocks. In Russia, 2014, more than 300 million tons of natural limestone were extracted and recycled to produce 209 million tons of lime coarse aggregate and 10 million tons of lime binders [17, 18]. The main component of limestone powder is calcium carbonate. It does not possess pozzolanic activity [19], but its use in SCC improves the deformability and viscosity, as well as reduction porosity [20]. Partial replacement of cement by limestone filler brings the enhancement in fluidity and a reduction of the yield stress [21].

The amount of limestone powder in cementitious materials can vary from 10 to 50 % [22]. Due to positive influence on the properties of SCC and economic benefits the limestone powder is a major component of many SCC mixtures [23]. Some research has been conducted regarding the properties of limestone powder in self-compacting concrete in recent years. However, most of the previous studies are limited or contain compositions with different quantity of the filler. The aim of this study is to establish the optimum quantity of limestone powder in SCC and its influence on technological and performance properties.

Materials, methods and mixture proportioning

Cement

The cement used in this study was Ordinary Portland Cement type CEM I 42.5 N Holcim Rus in accordance with [24]. Mineral content was: C_3A = 7.2 %, C_3S = 60.8 %, C_2S = 13.7 %, C_4AF = 10.0 % with specific surface area equal to 3600 cm^2/g. Chemical composition is presented in Table 1.

Table 1. Chemical composition of CEM 42.5 N

Component	**Percentage**	**Component**	**Percentage**
SiO_2	18.6	TiO_2	0.3
Al_2O_3	4.5	P_2O_5	0.1
CaO	63.6	SO_3	3.1
Fe_2O_3	3.1	Na_2O	0.2
MgO	3.2	K_2O	0.6

Mineral filler

The limestone powder was sourced from limestone quarry Saltykovskoe field, grinded in laboratory mill to a specific surface area equal to 3500 cm^2/g. Chemical composition of limestone powder is presented in Table 2.

Table 2. Chemical composition of limestone powder

Component	**Percentage, %**					
Limestone powder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Loss on ignition
	0.79	0.45	0.72	54.94	0.48	42.62

Aggregates

Crushed granite with a maximum size of 20 mm according to [25], specific gravity of 2.68 kg/m^3 and water absorption of 0.2 % according to [26] was used as coarse aggregate. Quartz sand was used as fine aggregate with specific gravity equal to 2.63 kg/m^3 with the fineness modulus of 1.2. The particle size distributions of both sand and crushed granite, obtained by sieving, are shown in Figures 1 and 2.

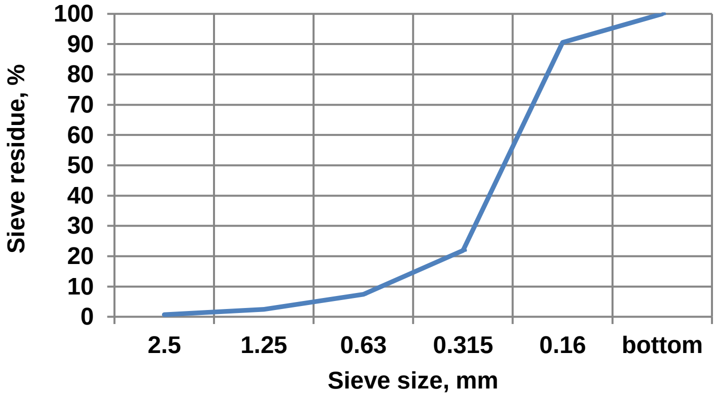

Fig. 1. Grading of fine aggregate

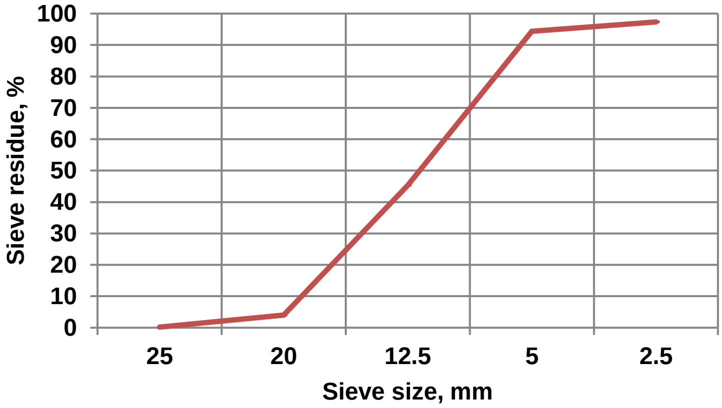

Fig. 2. Grading of coarse aggregate

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Chemical admixture

To adjust the workability of concrete mixture, maintain its dispersing effect during the time, required for transport and application, a superplasticizer based on polycarboxylate ethers Sika ViscoCrete 5-800 was used in accordance with [27, 28].

Evaluation of self-compactability

At the beginning of the experiment preliminary composition of self-compacting concrete with the following characteristics presented in Table 3 was developed. It was experimentally determined that the dosage of superplasticizer using slump-flow test on the paste [29] until the rheological parameters attained satisfactory level (660–750 mm). Necessary correlation between limestone powder, coarse aggregate and fine aggregate is based on requirements of self-compactability [30] and terms of concrete mixtures pumpability [31].

Trial batches of SCC with simultaneous adjustment were produced. The weights of constituent materials for producing one cubic meter of SCC mixtures, calculated using the absolute volume method.

Table 3. Preliminary compositions of the mixture

Material	**Unit mass (kg/m^3)**
CEM I 42.5 N	480
Limestone powder	190
Quartz sand	720
Crushed granite	765
Water	170
PCE SP Sika ViscoCrete 5-800	5.8

Mathematical planning method

The obtained SCC composition was corrected by using three-factor mathematical planning method. A compositional plan for a B_3-type cube was adopted for the implementation of the experiment. The factors of variation were: quantity of Portland Cement in kg/m^3; quantity of limestone powder in % by weight of Portland Cement; quantity of chemical admixture Sika ViscoCrete 5-800 in % by weight of Portland Cement. Other parameters remained unchanged. The zero level of variation was adopted for the preliminary composition.

Evaluation of hardened properties

The cube samples 100 x 100 x 100 mm were cased in accordance with [32, 33, 34] from each composition with no compaction. Demolding of the cubes was carried out 24 hours after casting. The cubes were placed in a 20 °C water curing tank until tests. The compressive strength of each cube was measured according to [35] at the age of 28 days.

Frost resistance and water permeability

Frost resistance was determined in accordance with [36] by third accelerated method (freezing and thawing in 5 % aqueous solution of NaCl, temperature of freezing was -50 °C) on cube samples 100 × 100 × 100 mm at the age of 28 days by placing samples in a 20 °C water curing tank. Water permeability was determined by “wet spot” method following [37] at the age of 28 days.

Results and Discussion

Optimization of the compressive strength of SCC

The levels of variation factors are shown in Table 4. The results of the compressive strength at 28 days are shown in Table 5.

Table 4. Levels and intervals varying factors

Factor			Levels varying factors			Intervals varying factors
Parameter	Description					
	Natural	Code	+1	0	-1	
Quantity of CEM I 42.5 N, kg/m^3	X_1	x_1	570	480	390	90
Quantity of Limestone powder, mass proportion of PC	X_2	x_2	0.5	0.4	0.3	0.1
Quantity of PCE SP Sika ViscoCrete 5-800, % of PC	X_3	x_3	1.4	1.2	1	1

Table 5. Matrix of the system response

No	**CEM I 42.5 N, kg/m^3**	**Limestone powder, in proportion of PC**	**PCE SP Sika ViscoCrete 5-800, in % of PC**	**Coded factor**			**Parameter of optimization**
				x_1	**x_2**	**x_3**	**Compressive strength in age of 28 days (MPa)**
1	2	3	4	5	6	7	8
1	390	0.3	1	-1	-1	-1	47.6
2	570	0.3	1	1	-1	-1	61.3
3	390	0.5	1	-1	1	-1	50.2
4	570	0.5	1	1	1	-1	67.7
5	390	0.3	1.4	-1	-1	1	44.3
6	570	0.3	1.4	1	-1	1	52.2
7	390	0.5	1.4	-1	1	1	49.9
8	570	0.5	1.4	1	1	1	68.0
9	390	0.4	1.2	-1	0	0	53.4
10	570	0.4	1.2	1	0	0	65.3
11	480	0.3	1.2	0	-1	0	47.7
12	480	0.5	1.2	0	1	0	49.6
13	480	0.4	1	0	0	-1	48.6
14	480	0.4	1.4	0	0	1	54.1

The number of experiments was 14, the number of repeated experiments was 3. The preparation of the concrete mixtures was performed in a laboratory mixer. The final mixing time after dosage of all materials was 90 seconds.

The final purpose of the data processing was to obtain the equation of regression by the number of defined characteristics with significant coefficients for the selected variables:

$$y = 52.06 + 6.98x_1 + 3.32x_2 + 7.3x_1^2 - 3.4x_2^2 + 0.93x_1x_2 + 0.83x_2x_3 \qquad (1)$$

The analysis of regression equations was carried out by a mathematical method. Graphic dependences are presented in Figures 3 and 4.

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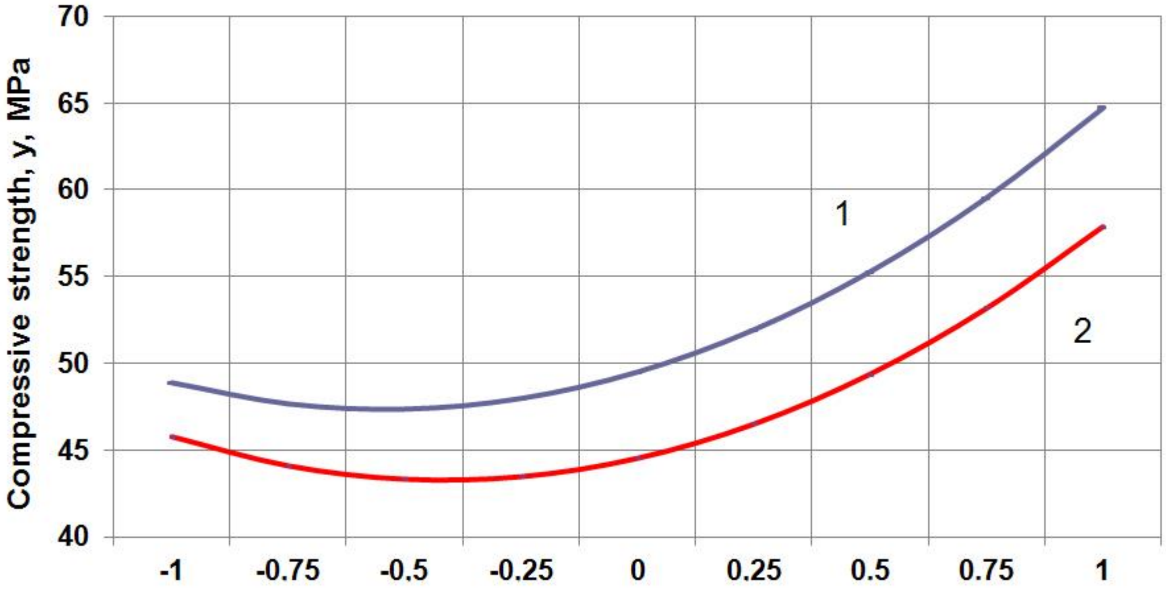

Figure 3. Dependency graphs of y = f (CEM I 42.5 N):
1 – dependency graph of y = f (CEM I 42.5 N) if $x_2 = 1$, $x_3 = 1$;
2 – dependency graph of y = f (CEM I 42.5 N) if $x_2 = -1$, $x_3 = 1$

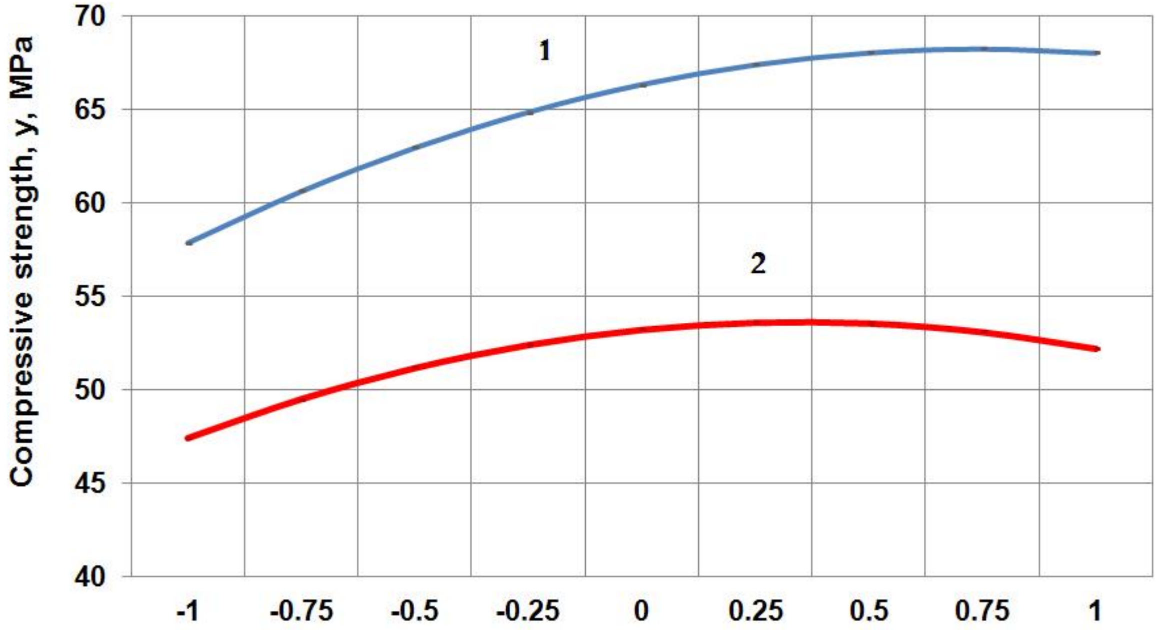

Figure 4. Dependency graphs of y = f (limestone powder):
1 – dependency graph of y = f (limestone powder) if $x_1 = 1$, $x_3 = 1$;
2 – dependency graph of y = f (limestone powder) if $x_1 = -1$, $x_3 = 1$

The composition with the highest compressive strength and optimum dosages of variable components was selected. The consumption of materials for one cubic meter based on the equation of regression (1) is presented in Table 6.

Table 6. Content of concrete mix by using mathematical planning method

Weights of the materials for one cubic meter of the concrete mixture (kg)						**Estimated density (kg/m^3)**	**Volume of aggregates**	**Estimated compressive strength (MPa)**
CEM I 42.5 N	Limestone powder	Quartz sand	Crushed granite	PCE SP	Water			
570	217	720	765	8	190	2462	0.56	68.24

Table 7. Properties of fresh concrete mixtures and hardened concrete

Density (kg/m^3)	**Slump flow (mm)**	**t_{500} (s)**	**Density of hardened concrete (kg/m^3)**	**Compressive strength (MPa)**				**Deviation from calculated strength, %**
				3	7	14	28	
2452	690	9	2438	41.3	56.5	59.3	69.0	+1.11

As it seen from the Table 6 and 7 the content of limestone powder in optimal SCC was 38% by weight of Portland cement.

Frost resistance and water permeability

Table 8. Frost resistance and water permeability of self-compacting concrete

Testing method	**The number of cycles of freezing/ thawing without failure and weight loss**	**Grade of freezing/ thawing**	**Sample size of cylinders (mm)**	**Water permeability (MPa)**	**Grade of water permeability**
Third rapid	55	F_2 400	d=150 mm h = 150 mm	1.6	W16

Conclusion

The test results showed possibility of using limestone powder in SCC. The results demonstrate positive influence of limestone powder on technological and performance properties. The obtained composition was optimized by mathematical planning method. It was determined that the optimal dosage of limestone powder in the developed SCC is 38 % to achieve technological requirements (690 mm of slump flow) with cement consumption equal to 570 kg/m^3. It was established that the adding of limestone powder in amount of 38 % together with the superplasticizer causes increasement of compressive strength in 3, 7, 14 and 28-day in the range of 41.3, 56.5, 59.3 and 69.0 MPa respectively that correlates with compressive strength of existing SCC with other fillers [38]. The introduction of limestone powder provides high density of concrete (2438 kg/m^3) that exceed existing results [39] and could enhance corrosion resistance and high durability. The developed SCC demonstrated 55 cycles of freezing/thawing, low rate of water permeability in the range of 1.6 MPa that can be explained by high water retention capacity on increase of the hydration degree by creating a high dense homogenous structure of the concrete.

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