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Environmentally-friendly self-compacting concrete

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Original scientific paper

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Environmentally-friendly self-compacting concrete

An experimental analysis of properties of self-compacting concrete, for both fresh and hardened states of concrete, is presented in the paper. Concrete mixes differed according to the type and quantity of mineral admixtures (metakaolin, fly ash). It was established that the addition of fly ash and metakaolin greatly improves mechanical properties and durability of self-compacting concrete, and is favourable to environment due to reduction in CO₂ emissions. Based on test results obtained, appropriate recommendations for practical application are given.

Key words:

CO₂ emission, fly ash, metakaolin, mineral admixtures, sustainability, self-compacting concrete, durability

Izvorni znanstveni rad

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Samozbijajući ekološki prihvatljivi betoni

U radu su eksperimentalno analizirana svojstva samozbijajućeg betona u svježem i očvrslom stanju. Betonske mješavine su se razlikovale prema vrsti i količini mineralnih dodataka (metakaolin, leteći pepeo). Utvrđeno je da dodatak letećeg pepela i metakaolina utječe na bitno poboljšanje trajnosnih i mehaničkih svojstava samozbijajućeg betona, te ekološki pozitivno djeluje na smanjenje emisije CO₂. Na temelju dobivenih rezultata ispitivanja dane su preporuke za praktičnu primjenu.

Ključne riječi:

emisija CO₂, leteći pepeo, metakaolin, mineralni dodaci, održivost, samozbijajući beton, trajnost

Wissenschaftlicher Originalbeitrag

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Selbstverdichtende umweltverträgliche Betone

In der Arbeit werden die durch experimentelle Versuche erforschten Eigenschaften von selbstverdichtendem Beton in frischem und in erhärtetem Zustand beschrieben. Verschiedene Betonmischungen im Bezug auf die Art und die Menge der zugegebenen Mineralstoffe (Metakaolin, Flugasche) wurden betrachtet. Es wurde festgestellt, dass die Zugabe von Flugasche und Metakaolin wesentlich die Haltbarkeit und die mechanischen Eigenschaften von selbstverdichtendem Beton verbessert und eine ökologisch positive Auswirkung auf die Verringerung der CO₂-Emission hat. Die erhaltenen Versuchsergebnisse werden als Grundlage der gegebenen Richtlinien für praktische Anwendungen angenommen.

Schlüsselwörter:

CO₂-Emission, Flugasche, Metakaolin, Mineralstoffe, Nachhaltigkeit, selbstverdichtender Beton, Haltbarkeit

1. Introduction

The self-compacting concrete is a new type of concrete that was initially developed and used in the late twentieth century. The basic characteristic of this concreting technology is that there is no need to use concrete compacting equipment when concrete is placed. Main advantages gained in this way are: reduced number of workers on construction site, faster realization of concrete works, much easier placing of concrete in zones characterized by dense reinforcement and/or in zones of complex cross section, good appearance of the outside visible surface of concrete, and reduced level of noise at the construction site. Due to its numerous advantages when compared to ordinary concrete, this type of concrete has very soon become widely recognised in practice. This is why some experts in the field of materials and technology emphasize that the self-compacting concrete ranks among the most notable discoveries that have been made over the past several decades [1-11].

One of basic directions in which the research on self-compacting concrete is currently oriented is the improvement of its properties, with simultaneous improvement of environmental acceptability and sustainability of this material. This is mostly achieved through the use of various mineral admixtures. The research related to self-compacting concrete has so far mostly been concentrated around the type II mineral admixtures (silica fume, fly ash, slag), which are at the same time regulated by existing standards and codes [12-18].

Fly ash is obtained as a byproduct in thermal power plants. One of main advantages of concrete improved with fly ash is its environmental acceptability thanks to lower CO₂ emissions.

Previous studies have revealed that the self-compacting concrete can be obtained by adding greater quantities of fly ash. This reduces the compressive strength, while durability and workability properties are mostly improved [16].

Metakaolin is a mineral admixture with a pozzolanic activity that is obtained by fabrication from kaolin clay. It is normally used in the quantity of 10 to 25 percent with respect to the total cement mass. Its environmental acceptability results from the fact that smaller CO₂ emissions are generated during metakaolin production, when compared to cement production. This information becomes even more significant in the light of the fact that 5-7 percent of the total worldwide CO₂ emissions are generated as a result of cement production. Test results have shown that mechanical and durability properties of ordinary concrete become better after addition of metakaolin. Research conducted to this effect has shown that early compressive-strength properties of the self-compacting concrete, and some of its durability properties (resistance to frost and salt, water permeability), are improved if metakaolin is added to concrete. Test production results have confirmed that the self-compacting concrete with 17.5 percent of metakaolin by cement weight is appropriate for production of prefabricated concrete elements. However, all durability properties of self-compacting concrete, and change of its properties over time, have not so far been tested [19-22].

Self-compacting concrete compositions with various mineral admixtures (fly ash, metakaolin) are designed in this paper. Fibrillated polypropylene fibres are used due to their positive influence on the reduction of crack width and spacing in green concrete, which contributes to better durability of concrete.

Table 1. Concrete mix compositions

Components [kg/m ³]	Concrete mix marks				
	SCC	SCC-F	SCC-M	SCC-FM	SCC-FMP
Cement	450	250	405	205	205
Fly ash	-	200	-	200	200
Metakaolin	-	-	45	45	45
Polypropylene fibres	-	-	-	-	1
Water	198	198	198	198	198
Water binding ratio	0,44	0,44	0,44	0,44	0,44
Superplasticiser	2,40	1,32	3,90	3,60	4,50
Mix stabiliser	0,77	0,77	0,77	0,95	0,88
Filler	150	150	150	150	150
Aggregate 0-4 mm	816	818	814	814	813
Aggregate 4-8 mm	328	329	328	328	327
Aggregate 8-16 mm	468	469	467	467	467

Components available on Croatian market have been used during experimental work in laboratory.

The influence of various admixtures on the properties of self-compacting concrete were analysed at fresh and hardened state of concrete. Test results were used to determine advantages of individual concrete compositions with regard to concrete properties in hardened state.

Mechanical and durability properties of the self-compacting concrete, with admixtures and without admixtures, were compared for the same water binding ratio.

The results obtained show that the use of fly ash and metakaolin in self-compacting concrete is quite justified. Based on these results, appropriate recommendations were given for practical use of individual mixes of self-compacting concrete.

2. Experimental work

2.1. Concrete mix compositions

Five concrete mixes were subjected to experimental analysis. Concrete mix compositions are presented in Table 1. All mixes had the same water-binding ratio (0.44) and the same quantity of binder. The three-fraction crushed aggregate was used in the mixes. The concrete composition was designed to meet environmental exposure classes XC4, XS3 and XD3, compressive strength class C50/60, and the time-dependent settlement criterion SF3 $t_{500} < 2.0$ sec (VS1).

The following marks were used for individual mixes:

- SCC: self-compacting concrete
- SCC-F: self-compacting concrete with fly ash
- SCC-M: self-compacting concrete with metakaolin
- SCC-FM: self-compacting concrete with fly ash and metakaolin
- SCC-FMP: self-compacting concrete with fly ash, metakaolin and polypropylene fibres.

2.2. Testing objectives and program

The objectives of the testing campaign were:

- design the self-compacting concrete composition using metakaolin and fly ash
- obtain experimentally the self-compacting concrete with various mineral admixtures (fly ash, metakaolin) using components available on Croatian market
- determine influence of fly ash on self-compacting concrete properties in fresh and hardened state
- determine influence of metakaolin on self-compacting concrete properties in fresh and hardened state
- determine influence of polypropylene fibres on self-compacting concrete properties in fresh and hardened state
- determine influence of fly ash, metakaolin, and polypropylene fibres combination on self-compacting concrete properties in fresh and hardened state

- determine an optimum mix of self-compacting concrete with mineral admixtures
- compare properties of ordinary self-compacting concrete with those of self-compacting concrete with mineral admixtures and polypropylene fibres
- determine influence of the age of samples (28 and 90 days) on the mechanical and durability properties of self-compacting concrete with and without mineral admixtures.

The following properties of the fresh concrete mixes were tested:

- density (HRN EN 12350-6)
- voids content (HRN EN 12350-7)
- temperature (HRN U.M1.032)
- consistency by flow table test (HRN EN 12350-8)
- V-funnel test (HRN EN 12350-9)
- L-box test (HRN EN 12350-10)

The flow table method is primarily used to test the filling property of the self-compacting concrete. The total diameter the concrete takes up by spreading is measured, and the time needed for the concrete to reach the horizontal diameter of 50 cm is determined. The L-box method is used to define the passing properties of the self-compacting concrete. The V-funnel method is used to determine the viscosity and filling capacity by measuring the time needed for the self-compacting concrete to flow out of the V-funnel.

The following test methods were used test properties in hardened state:

- compressive strength (HRN EN 12390-3)
- bending strength (HRN EN 12390-5)
- ultrasound pulse velocity (HRN EN 12504-4)
- capillary absorption (HRN U.M8.300)
- chloride diffusion (NT BUILD 492).

The experimental work was carried out in the laboratory of the Department for Materials of the Faculty of Civil Engineering – University of Zagreb.

2.4. Preparation technology and sample curing

All mixes were prepared in the laboratory mixer 100 l in capacity.

After placing, the samples were freed from mould at 1 day, and the testing to be conducted after one day was performed (compressive strength). Other samples were cured in the wet chamber until the age of 28 and 90 days when the remaining tests of mechanical and durability properties were conducted.

2.5. Components

The Portland cement CEM 142.5 R was used in all mixes.

A three-fraction aggregate made of crushed dolomite was used. The filler of dolomite origin, with most grains passing

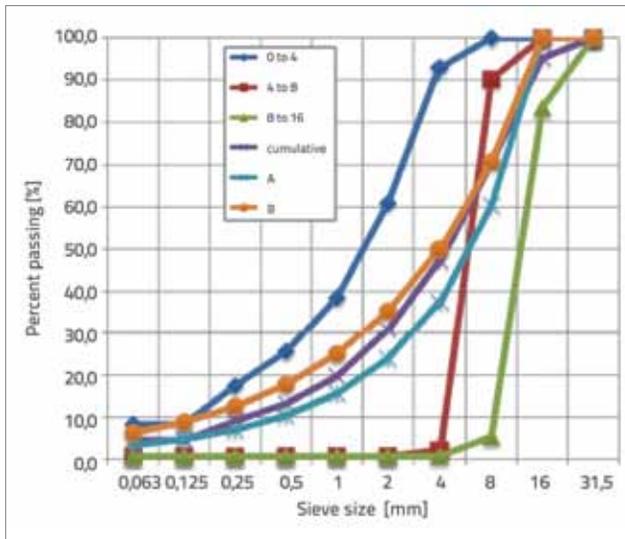


Figure 1. Grading of aggregate fractions

Table 2. Filler grading

Sieve [mm]	0.063	0.09	0.125	0.25	0.5
Passing [%]	64	81	91	99	100

Table 3. Properties of individual components

Property	Components			
	CEM I 42,5 R	Fly ash	Metakaolin	Filler
Ignition loss	4,47 %	3,52 %	1,36 %	47,58 %
SO ₃	3,07 %	1,04 %	0,080 %	0,050 %
SiO ₂	19,90 %	46,84 %	52,95 %	0,23 %
Fe ₂ O ₃	2,71 %	4,94 %	1,14 %	0,18 %
Al ₂ O ₃	5,38 %	27,67 %	41,17 %	0,31 %
CaO	60,23 %	9,65 %	-	30,38 %
MgO	2,87 %	2,79 %	-	21,84 %
Cl	0,030 %	0,008 %	0,008 %	0,013 %
Density	3,07 kg/dm ³	2,41 kg/dm ³	2,68 kg/dm ³	2,87 kg/dm ³

Table 4. Limit values for testing concrete in fresh state

Test method	Limit values	Class
Flow table test [mm]	550-650	SF1
	660-750	SF2
	760-850	SF3
Flow table test t ₅₀₀ [s]	<2	VS1
	≥2	VS2
L-box	≥0,80	PL1 (2 ribs), PL2 (3 ribs)
V-funnel [s]	<9,0	VF1
	9,0-25,0	VF2

through the 0.125 mm sieve, was used. The aggregate and filler grading is shown in Figure 1 and Table 2. Densities and chemical compositions of components are given in Table 3. Fibrillated polypropylene fibres 12 mm in length and 0.016 mm in diameter were used. The polycarboxylate superplasticiser and mix stabilizer were used as chemical admixtures.

3. Test results

3.1. Test results in fresh state

Fresh self-compacting concrete must have the following properties: filling ability, passing ability, and resistance to segregation. Limit values of test methods used for the self-compacting concrete in fresh state are presented in Table 4, while the results obtained are given in Table 5. The realization of individual tests is presented in Figure 2.

Test results for the fresh self-compacting concrete show that all mixes have properties that are typical for the self-compacting concrete. As to filling and passing abilities, all mixes comply with classes SF3, VS1, PL2 and VF1. The resistance to segregation was checked by visual inspection of all mixes, and it was determined that this requirements has also been met by all mixes. The reduction in density can

Table 5. Test results for fresh concrete

Test method	Unit	Concrete composition designations				
			SCC-F	SCC-M	SCC-FM	SCC-FMP
Flow table test	mm	760	790	760	785	775
Flow table test t_{500}	s	1,2	1,4	1,3	1,5	1,2
L-box	-	0,80	0,86	0,82	0,90	0,83
V-funnel	s	5,5	7,4	6,4	8,5	8,2
Air content	%	0,80	1,60	1,20	1,60	1,20
Density	kg/m ³	2490	2430	2480	2420	2410
Temperature	°C	22	23	21,8	23,5	23,6



Figure 2. Self-compacting concrete testing by L-box (on the left) and by flow table (on the right)

be noted in self-compacting mixes with fly ash. This is due to lower density of fly ash when compared to concrete. The density of the mix with metakaolin is similar to that of the reference mix of the self-compacting concrete.

3.2. Test results in hardened state

Results obtained by testing mechanical and durability properties of self-compacting concrete are presented in Table

Table 6. Test results in hardened state

Tested property	Unit	Age of sample	SCC	SCC-F	SCC-M	SCC-FM	SCC-FMP
Compressive strength	MPa	1 day	40,1	16,9	38,6	11,9	12,8
		28 days	62,5	54,8	80,8	61,8	64,0
		90 days	67,4	69,4	83,0	64,8	69,7
Bending strength	MPa	28 days	5,4	4,8	6,9	7,0	4,8
Density	kg/dm ³	28 days	2,46	2,41	2,47	2,39	2,39
Longitudinal wave velocity	m/s	28 days	5077	4850	5056	4713	4751
Dynamic modulus of elasticity	GPa	28 days	67,8	60,4	67,7	56,6	57,5
Chloride diffusion coefficient	10 ⁻¹² m ² /s	28 days	9,83	6,40	1,73	2,17	1,51
		90 days	9,17	1,11	1,31	0,44	0,22
Capillary absorption coefficient, after 1 h	kg/m ² h ^{0,5}	28 days	1,09	0,90	0,65	0,60	0,44
		90 days	0,55	0,40	0,42	0,28	0,26
Capillary absorption coefficient, after 24 h	kg/m ² h ^{0,5}	28 days	0,63	0,43	0,37	0,25	0,23
			0,31	0,26	0,28	0,23	0,20

6. Diagrams showing capillary absorption obtained by testing at 28 and 90 days are presented in Figures 3 and 4.

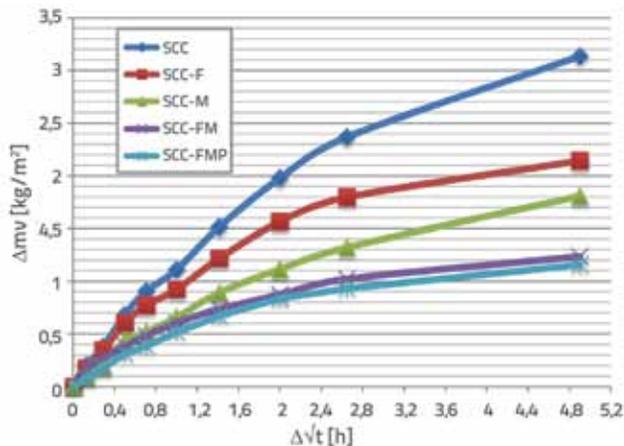


Figure 3. Graphical presentation of capillary absorption at 28 days

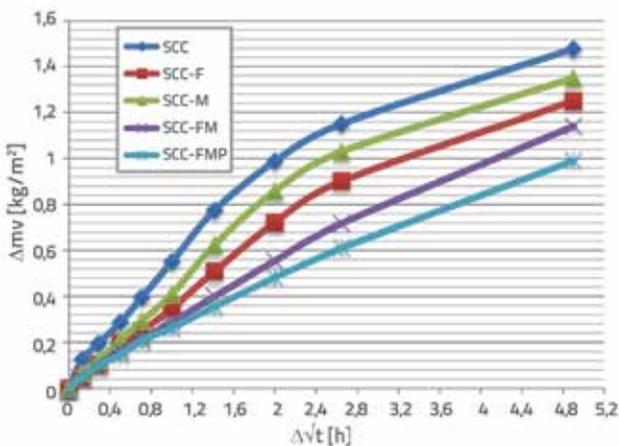


Figure 4. Graphical presentation of capillary absorption at 90 days

4. Analysis of test results

4.1. Influence of fly ash on self-compacting concrete properties

If 45 % of fly ash by cement weight is added to the self-compacting concrete, the compressive strength of concrete is reduced at 1 and 28 days, while it is increased at 90 days. The compressive strength of the self-compacting concrete with 45 % of fly ash by cement weight reduces after 1 day by 47 percent, and by 12 percent after 28 days, while after 90 days the compressive strength exceeds by 3 percent that of the self-compacting concrete without fly ash. These results are explained by pozzolanic reaction of fly ash that takes place after hydration of cement. After a longer time period, the concrete with fly ash can, with proper cure, attain mechanical properties of concrete without fly ash.

Test results obtained in hardened state show that the density in the hardened state reduces when fly ash is added into the self-compacting concrete. The fly ash greatly improves

durability properties with respect to the chloride diffusion and water absorption coefficients. When added to the self-compacting concrete, the fly ash greatly improves durability properties at 90 days, when compared to such properties at 28 days.

4.2. Influence of metakaolin on self-compacting concrete properties

The compressive strength of the self-compacting concrete with 10 percent of metakaolin reduces after one day by 4 percent, increases by 29 % at 28 days, and increases by 23 % at 90 days, when compared to the self-compacting concrete without metakaolin. The bending strength of concrete with metakaolin increases by 28 %. This is explained by the rise in the cement matrix homogeneity due to addition of metakaolin, although this is not shown by the dynamic modulus of elasticity test results.

The chloride diffusion coefficient is improved by 5.7 times at 28 days and by 7 times at 90 days due to addition of metakaolin into the self-compacting concrete. The coefficient of capillary absorption is greatly improved after addition of metakaolin. The results obtained show that the durability and strength properties of self-compacting concrete are greatly improved after addition of metakaolin.

4.3. Influence of polypropylene fibres on self-compacting concrete properties

The influence of polypropylene fibres on self-compacting concrete properties can be seen in the analysis of results shown in Table 5. When compared to the mix SCC-FM, the compressive strength of the mix SCC-FMP is greater by 8 % at 1 day, 4 % at 28 days, and 8 % at 90 days. Unlike compressive strength where polypropylene fibres do not greatly influence concrete properties, the addition of fibres considerably improves the chloride diffusion coefficient.

4.4. Selecting an optimum self-compacting concrete mix with mineral admixtures

Based on the ultrasound pulse velocity results (>4500 m/s), it can be concluded that all types of self-compacting concrete belong to high-quality concretes. The greatest velocity was obtained by the mix SCC-M which also has the greatest compressive strength, and so it can reasonably be stated that the said mix is also characterized by the most homogeneous structure.

With regard to all test results for hardened state, it can be stated that the mix SCC-FMP is in fact an optimum mix. High compressive strength values at 28 and 90 days were obtained for this mix, as can be seen in Figure 5. The mix marked SCC-FMP has the best values for the chloride diffusion coefficient (Figure 6) and capillary absorption coefficient at 28 and 90

days. As mineral admixtures are mostly added to the concrete in order to improve its durability, the durability criteria in hardened state can be taken as relevant for selection of an optimum mix.

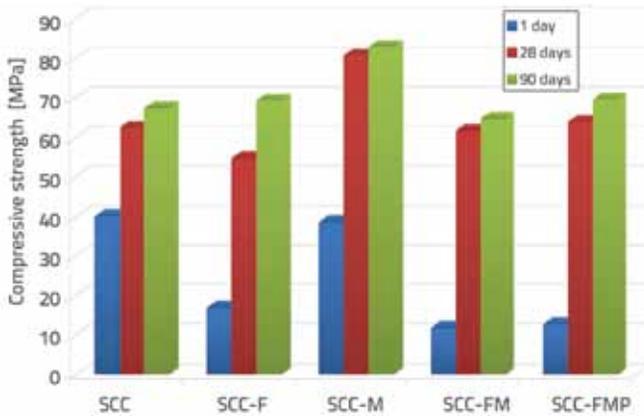


Figure 5. Compressive strength at 1, 28 and 90 days



Figure 6. Chloride penetration depth for the mix SCC (left side) and mix SCC-FMP (right side)

4.5. Influence of sample age on mechanical properties and durability of self-compacting concrete

The greatest increase in compressive strength at 90 days, compared to 28 days (27 %), was registered at the mix SCC-F. The comparison of chloride diffusion coefficients for mixes

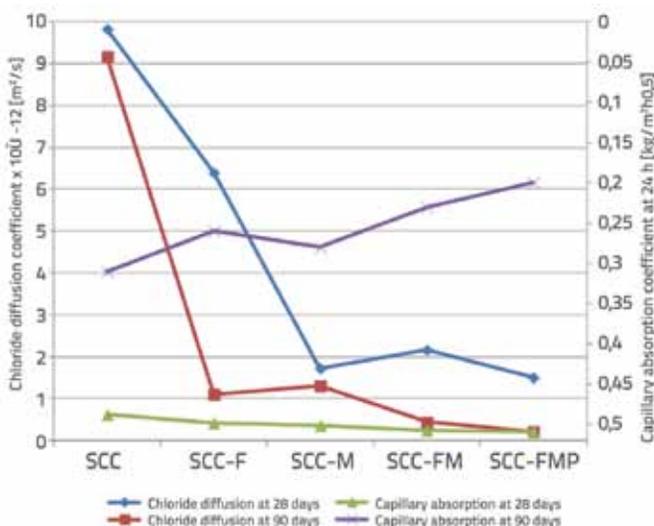


Figure 7. Comparison of chloride diffusion and capillary absorption coefficients at 28 and 90 days

with admixtures has revealed that in case of the mix SCC-F the chloride diffusion coefficient was reduced by 5.8 times at 90 days with respect to 28 days, by 1.3 times in case of the mix SCC-M, by 1.1 times in case of the mix SCC, by 4.9 times in case of the mix SCC-FM, and by 6.9 times in case of the mix SCC-FMP. In addition, mixes with admixtures have attained better capillary absorption coefficients at 90 days compared to 28 days (cf. Figure 7). The smallest coefficients were attained by the mix SCC-FMP. The mix SCC-M obtained better capillary absorption coefficients at 28 days compared to mix SCC-F, while the mix SCC-F had better coefficients than the mix SCC-M at 90 days. It can be concluded from the analysis of chloride diffusion and capillary absorption coefficients that metakaolin has a greater influence on improvement of durability properties at 28 days compared to fly ash (although it is added in much smaller quantities than the fly ash), while fly ash has a greater influence on improvement of durability properties at 90 days.

4.6. Recommended practical use of results

Considering that the compressive strength is the only basic property of concrete, it is also necessary to define an optimum quantity of mineral admixtures (fly ash and metakaolin). At that, the intended use of the self-compacting concrete must also be taken into account. For instance, if the self-compacting concrete is used for prefabricated prestressed concrete elements, or for the remedy of degraded reinforced-concrete structures, then it is not recommended to use the self-compacting concrete with a higher fly ash content. In such cases, the use of self-compacting concrete with metakaolin, or without any admixtures, is recommended.

On the other hand, a greater quantity of fly ash is desirable as it can reduce hydration heat during concreting of massive concrete elements. The self-compacting concrete to be used in an aggressive environment should be improved by metakaolin, or by the fly ash and metakaolin combination.

The self-compacting concrete with fly ash, metakaolin and polypropylene fibres is recommended for aggressive environments, and especially for unfavourable thermohygrometric conditions due to the ability of polypropylene fibres to reduce green concrete cracking. Besides the above mentioned, the addition of mineral admixtures (fly ash and metakaolin) also reduces the quantity of cement in concrete, which is a direct contribution to the reduction of CO₂ emissions. It can therefore be said that this type of self-compacting concrete is environmentally acceptable for use in civil engineering.

For all above mentioned applications, one should also take into account the advantages that are gained through the use of the self-compacting concrete technology, when compared to ordinary concrete.

One of obstacle hindering a wider use of metakaolin is the lack of standard that would specify the properties, control of conformity, and other parameters relating to this material.

The study conducted in this paper shows that the addition of metakaolin greatly improves certain properties of concrete, which is an important reason for speeding up the process aimed at adoption of the metakaolin standard.

5. Conclusion

After analysis of results obtained by testing properties of the self-compacting concrete with different mineral admixtures (fly ash, metakaolin), designed for environmental exposure classes XC4, XS3, XD3, the following conclusions can be made:

- Based on results obtained by testing mixes in fresh state, it was established that the influence of mineral admixtures on the workability, passing ability, filling ability and resistance to segregation, is quite visible. The self-compacting concrete with admixtures is characterized by better properties compared to similar self-compacting concrete without admixtures.
- The compressive strength testing has revealed a considerable influence of fly ash on the reduction and, in case of metakaolin, on the increase, of compressive strength at 28 days, but also on the reduction after 1 day.
- The self-compacting concrete with admixtures has a better capillary absorption coefficient and a better chloride diffusion coefficient, when compared to the self-

compacting concrete without admixtures, for similar water binding ratio and binder quantity.

- The metakaolin improves durability of self-compacting concrete at 28 days to a greater extent than the fly ash, although it is added in a much smaller quantity than the fly ash.
- The fly ash improves the durability of the self-compacting concrete at 90 day to a greater extent than the metakaolin.
- Through addition of mineral admixtures, the self-compacting concrete has become a more environmentally acceptable material due to reduced quantity of cement, which results in smaller CO₂ emissions into atmosphere during cement production.
- The addition of polypropylene fibres into the self-compacting concrete mix containing the fly ash and metakaolin improves the chloride diffusion coefficient.

The possibility of combining mineral admixtures in the self-compacting concrete opens up new areas for practical application. One of significant preconditions for this is the establishment of a uniform standard for metakaolin.

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Research of asphalt layer bonding in Lithuanian pavement structures

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Preliminary note

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Research of asphalt layer bonding in Lithuanian pavement structures

The strength and durability of road pavement structures are directly influenced by the way in which asphalt layers are bonded. An insufficient bond between pavement layers leads to wearing, tearing, pavement deterioration, and cracking, and the pavement life span is reduced. The quality of bond between pavement layers was determined by direct shear test, using the so called Leutner method, without normal stress in specimen. Test samples were taken at various locations along the Lithuanian road network, from pavements characterized by standard asphalt structure, and reinforced asphalt structure in which geosynthetic materials are used in interlayers

Key words:

asphalt pavement, bond between pavement layers, Leutner method

Prethodno priopćenje

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Istraživanje veziva asfaltnih slojeva kolničkih konstrukcija u Litvi

Način povezivanja slojeva asfaltna kolničke konstrukcije izravno utječe na čvrstoću i trajnost kolnika. Ako veza nije pravilno izvedena, kolnik postaje sklizak, dolazi do habanja, pucanja, propadanja kolnika i pojave pukotina te smanjenja vijeka trajanja. Kvaliteta veze između slojeva kolnika određena je direktnim ispitivanjem na smicanje, takozvanom Leutnerovom metodom bez pojave normalnog naprezanja u uzorku. Uzorci za ispitivanja uzeti su na različitim lokacijama cestovne mreže u Litvi, i to iz kolnika s klasičnom asfaltnom konstrukcijom te s pojačanom asfaltnom konstrukcijom primjenom geosintetika u međuslojevima.

Ključne riječi:

asfaltni kolnik, veza slojeva kolničke konstrukcije, Leutnerova metoda

Vorherige Mitteilung

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Untersuchung des Verbunds von Asphaltschichten in litauischen Fahrbahnstrukturen

Der Verbund von Asphaltschichten der Fahrbahnstruktur hat einen direkten Einfluss auf die Festigkeit und die Haltbarkeit der Fahrbahn. Unsachgemäß ausgeführte Schichtenverbunde können eine rutschige Oberfläche der Fahrbahn verursachen, während möglicherweise auftretende Verschleißung, Rissbildung und andere Beschädigungen zu einer Verringerung der erwarteten Lebensdauer führen können. Die Qualität der Schichtenverbunde des Straßenbelags ist durch Abscheversuche ermittelt, mit Hilfe der sogenannten Leutner-Methode, die ohne das Auftreten von Normalspannungen ausgeführt wird. Versuchsproben sind an verschiedenen Standorten des Straßennetzes in Litauen entnommen worden, und zwar sowohl für Fahrbahnen mit klassischen Fahrbahnstrukturen, als auch für Asphaltbeläge, die durch die Anwendung von geosynthetischen Materialien in den Zwischenschichten verstärkt wurden.

Schlüsselwörter:

Asphaltfahrbahn, Schichtenverbunde der Fahrbahnstruktur, Leutner-Methode