Acta Technica Napocensis: Civil Engineering & Architecture Vol. 57, No. 2 (2014)
Journal homepage: http://constructii.utcluj.ro/ActaCivilEng

Durability of Self-Compacting Concrete with Fly Ash Addition

Alexandra Coșa[*1], Camelia Negruțiu[2]

[1,2] *Technical University of Cluj-Napoca, Faculty of Civil Engineering. 15 C Daicoviciu Str., 400020, Cluj-Napoca, Romania*

(Received 6 August 2014; Accepted 17 October 2014)

Abstract

The present paper presents the influence of fly ash on the properties of fresh concrete and the durability of self-compacting concrete (SCC). Using fly ash as a partial cement replacement reduces both production costs and pollution due to the impressive amount of CO_2 from cement production. In terms of concrete performance, fly ash reduces permeability and improves workability, with a significant increase of long term compressive strength. Seven compositions were designed in the process of obtaining the necessary workability requirements of SCC. The final composition was obtained with a substitution of 65% fly ash of the cement amount and a water/binder ratio of 0.36. Once obtained, the fresh state properties were tested, namely the flowability, viscosity, and the passing ability. For the study of self-compacting concrete durability, concrete samples were tested for the action of chloride, sulfate and carbonation.

Rezumat

Această lucrare prezintă influența cenușii zburătoare asupra proprietăților betonului proaspăt, precum și asupra durabilității betonului autocompactant (BAC). Înlocuirea unei părți de ciment cu cenușă reduce atît costurile de producție cât și poluarea datorită cantității impresionante de CO_2 rezultate din producția cimentului. În ceea ce privește performanța betonului, acestea reduc considerabil permeabilitatea, îmbunătățesc lucrabilitatea, atingând rezistențe mari în timp. Au fost proiectate șapte rețete de beton până când s-a obținut un beton care să satisfacă cenrințele de lucrabilitate pentru betonul autocompactant. Rețeta finală s-a obținut cu un adaos de cenușă de 65% din cantitatea de ciment și un raport A/L de 0.36. Odată obținută rețeta de beton autocompactant,au fost testate prprietățile în stare proaspătă, și anume răspândirea din tasare, timpul de curgere și abilitatea de trecere. Pentru studiul durabilității betonului autocompactant, s-au turnat probe de beton care au fost supuse încercărilor pentru determinarea rezistenței la acțiunea ionilor de clor, a sulfaților și rezistența la carbonatare.

Keywords: self-compacting concrete, fly ash, workability, compressive strength, durability, sulfate attack, chloride penetration, carbonation

1. Introduction

Over the last years the problem of durability of concrete structures has been debated intensively, but it is difficult to define durability, since concrete with a given set of properties will endure without

[*] Corresponding author: Tel.:0741979933
E-mail address: alexandracosa89@yahoo.com

important damage for centuries in one specific environment and could be destroyed in a few years in another. [1] Therefore, the latest industrial and economic competition trends of achieving sustainability, low costs and environmental safeguarding have pushed the concrete research in very specific directions. As a consequence, low porosity, low water/binder ratio, low costs and low cement content are a must for new types of concrete, as the one developed in the current study.

Fly ash is one of the most important industrial waste products which, due to its chemical composition and hydraulic properties, can be source for new constituent materials in various fields. Fly ash from coal-burning electric power plants is obtained from the rapid combustion of coal dust at temperatures from 1200 to 1600^{o} C, with a strong ecological impact because of the large quantity resulted and whose storage affects large areas of infields. Particle size and shape characteristics of fly ash are dependent upon the source of the coal, but the majority of fly ash particles are spherical in shape with a diameter between 1 and 100 μm. Therefore, the addition of the fly ash to the concrete composition not only solves an ecological problem and reduces overall production costs of concrete, but improves concrete short and long term performance. [2, 3]

Self-compacting concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. The industrial development of SCC starts in the late 1980's in Japan, although the concrete that requires little vibration has been used in Europe since the early 1970's. Because of its self-consolidation ability, the SCC has a high level of homogeneity, minimal concrete voids and uniform concrete strength, avoiding the human errors that can interfere when vibrating the concrete. [4]

Basic workability requirements for successful casting of SCC consist in obtaining a balance between deformability and stability, avoiding the blockage of concrete flow. Using fly ash as an additional cementing material will improve the workability and cohesiveness and will reduce segregation and the quantity of expensive water reducer admixture. [5, 6] Furthermore, fly ash used as a cement replacement affects the compressive strength of concrete at early ages, but after the age of 28 days, the late pozzolanic reaction contributes to the strength development. The main product resulted from the reaction of fly ash with the calcium hydroxide and the alkali hydroxide, is the same with the hydration product of the Portland cement, the C-S-H (calcium silicate hydrate), responsible with the strength development. [7-9]

Solely the short term properties of the concrete are unfortunately not satisfactory. Long term, environmental behavior of concrete structures must be investigated before new concrete compositions are released for industrial use. For example, chloride-induced reinforcement corrosion is the most important degradation process for reinforced concrete. Concrete usually provides physical and chemical protection to the reinforcement from penetrating chlorides which may cause steel depassivation and corrosion. The main sources of chlorides are the de-icing salts, seawater and the industrial chemical compounds like HCl and $CaCl_{2.}$ [10] The chloride resistance decreases with the permeability of concrete, and due to the lower permeability of fly ash concrete, the chloride resistance improves. [11, 12] Likewise, sulfates from groundwater and seawater penetrate into concrete and react with the hydrated cement, leading to the production of gypsum and ettringite, and consequently to the loss of the efficiency of the C-S-H. [13] Low calcium fly ash is known to improve the sulfate resistance by the reduction of the total amount of C_3A in the concrete mix, and by the pozzolanic reaction, a refined calcium silicate hydrate binder matrix is formed. [14]. Another type of chemical attack and also the most common is carbonation, which basically is the chemical reaction of the hydrated cement paste with CO_2 molecules, diffusing from the air into the concrete. By this reaction, carbonates are formed and OH^- ions are consumed. This leads to a drop of the pH value and, once the value is below 9, the reinforcement becomes depassivated. [15] Some researchers have reported that fly ash concretes carbonates faster than traditional concrete, even if the permeability is improved and the porosity is reduced [16, 17].

2. Scope

This study is focused on the development of a low cost, high performance self compacting concrete with high volume fly ash used as 65% cement replacement. The fresh state properties of the concrete are investigated, as well as the concrete behavior to certain durability aspects, such as chloride and sulfate attack and carbonation.

3. Experimental program

3.1. Materials

The cement type used in the experiment is CEM I 52.5 R, according to SR EN 197-1. 16 mm maximum size natural aggregates were used as 0-4 mm sand and 4-8, 8-16 mm coarse aggregate. The amount of fine sand with particle size smaller than 0.125 mm was low. A polyether carboxylates high rage water reducer (HRWR) was also use in the concrete mix. The source of the fly ash is The Electrical Powerplant Zalau, Romania (*Uzina Electrică Zalău).*

3.2. Mix proportions

There is no standard method for SCC mix design, most of the methods being developed to satisfy different technical, economic and ecological criteria. Some mix design methods were developed by research institutes and in private practice. Among them, the Okamura- Ozawa method is based on the minimum volume between particles. The first step in the design process is the selection of constituent materials and the required performance. Based on the required performance the powder and the paste volume are determined. Then the aggregates volume is calculated and determined the sand/gravel ratio. It is recommended to determine the aggregate particle size distribution. Once all materials were proportioned, the mix properties should be verified and if necessary, adjustments to the mix composition should then be made. [18] The same method was applied by the authors of the current study, sequentially, in a process of 7 concrete mixes which are summarized in Table 1.

Table 1: Concrete mixes

Material		Mix Pr	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Cement CEM I 52,5R	kg/m^3	360	360	360	360	370	370	370	370
Fly ash	kg/m^3	126	126	180	180	180	180	222	240
Water	l/m^3	156	156	171	173	193	231	222	222
HRWA	l/m^3	6	12	12	12	12	15	15	15
Total Aggregates	kg/m^3	1707	1707	1596	1567	1562	1562	1562	1562
Sand 0/4	kg/m^3	915	915	602	1051	988	988	988	988
Gravel 4/8	kg/m^3	396	396	497	258	287	287	287	287
Gravel 8/16	kg/m^3	396	396	497	258	-	-	287	287
Water/Cement ratio		0.43	0.43	0.48	0.48	0.52	0.62	0.60	0.60
Water/Binder ratio		0.32	0.32	0.32	0.32	0.35	0.42	0.38	0.36
HWRA	%	1.6	3.4	3.4	3.4	3.4	4	4	4
Cement replacement by fly ash	%	35	35	50	50	49	49	60	65

3.3 Testing methods

Workability was tested, according to "The European Guidelines for Self Compacting Concrete", Annex B [2] for the following characteristics: slump-flow test for flowability; V –funnel test and the T500 test for viscosity; L-box test for passing ability.

Compressive strength was tested on 150x150x150 mm cube samples to determine the concrete class, and in order to make a comparison between the concrete mixes, 142x142x142 mm cube samples were tested.

To determine the chloride resistance The Rapid Chloride Permeability Test (RCPT) was used, which measures chloride ion migration or the electrical conductance of concrete. In this method, a potential difference of 60 v DC is maintained across the ends of 51 mm thick slice of a 28 days old concrete cylinder, one of which is immersed in a sodium chloride solution, the other in a sodium hydroxide solution. The amount of electrical current passing through the concrete during a six-hour period is measured and the total charge passed, in coulombs, is used as an indicator of the resistance of the concrete to chloride ion penetration.[19]

The simulation of natural environmental conditions, when deicing salts are applied for traffic safety was also intended in this study. Even if the concrete by itself is generally unaffected by the presence of the chlorides, the danger lying in the corrosion of the reinforcement, the precipitation salts may cause tensions on the concrete pores and thus, exfoliations in the weak zones, usually around aggregates. Therefore, three 100x100x100 mm cube specimens were immersed in a 20% sodium chloride (NaCl) solution for 7 days. Before the specimens were immersed in solution, they were cured for 28 days in water at 20±3^{o} C. To measure the chloride penetration depth, the specimens were spliced and sprayed with a 1% solution of silver nitrate ($AgNO_3$). Chloride reacts with silver and produces silver chloride, a white colored substance. Meanwhile in the absence of the chlorides, the silver reacts with the hydrates available in concrete, producing a brownie color.

In order to simulate a sulfate exposure, a magnesium sulfate (MgO_4S) solution of 10% concentration by mass was prepared. The sulfate solution and three 100x100x100 mm cube specimens was filled into a plastic container and placed for 7 days in a room with 20±3^{o}C temperature. After the exposure period, the compressive strength of the specimens were tested and compared to the reference samples to evaluate the loss of strength.

The carbonation test was performed by exposing 100x100x100 mm cube specimens to emission exhausting gasses for 20 days, in order to simulate an accelerated carbonation environment. The depth of the carbonation depends on colorless phenolphthalein indicator, which is sprayed onto the cross-section of the split specimens, showing a change in color depending on the pH factor.

4. Results and Discussion

4.1 Workability

In order to increase the workability, the quantity of the HRWA used in the initial mix was raised from 1.6% to 3.4% and the water/binder ratio from 0.32 to 0.36. In terms of high performance/high strength concrete a low W/B ratio of 0.36 is a common, whereas for ordinary concrete a W/B = 0.4 with the same quantity of cement usually renders a C50/60 rather viscous concrete class. For the self consolidating concrete in study, the relatively high water/binder ratio increased the workability, but leaded to bleeding and segregation. Until we obtained a balance between stability and deformability, we adjusted the proportion of the cement, fly ash, water and admixture. A balance was reached in the Mix 7, made with a cement content of 370 kg/m^3, a water/binder ratio of 0.36, 65% cement replacement by fly ash and 4% HRWA.

In Table 2 are given the values for the slump-flow consistency, the T500 and V-funnel flow time and the passing ability of the concrete mixes. Classification used in the specification of SCC and their abbreviation are the following: consistence classes expressed by slum-flow for SF1 to SF3; viscosity classes expressed by T500 for VS1 to VS2; viscosity classes expressed by V-funnel time for VF1 to VF2; passing ability classes expressed by L-box passing ability test for PL1 to PL2.

Figure 1. Slump-flow for preliminary mix

Figure 2. Slump-flow for mix 7

Table 2: Results of fresh state properties of concrete

Concrete mixes	**Slump flow (mm)**	**T500 flow time (s)**	**V-funnel flow time (s)**	**Passing ability using L-box (H2/H1)**
Mix 1	440	-	-	-
Mix 2	590	10	-	-
Mix 3	430	-	-	-
Mix 4	680	7	-	-
Mix 5	620	6	-	-
Mix 6	630	8	-	-
Mix 7	640	7	14	0,9
Classification of the SCC according to the European Guideline [2]	***SF1 550-650***	***VS1 <2.0***	***VF1 <9.0***	***PL1 ≥0.80 2 bars***
	SF2 660-750	***VS2 ≥2.0***	***VF2 9-25***	***PL2 ≥0.80 3 bars***
	SF3 760-850			

Fly ash has a positive influence on the workability of concrete, and generally resulted in a reduction of water and superplasticizer for a similar flow diameter. Furthermore, for similar workability, increasing the water/binder ratio reduces the amount of superplasticizer required but leads to bleeding and segregation. The preliminary mix displayed a very low workability (Figure 1). Even if the preliminary mix was calculated with the Okamura-Ozawa method, and satisfied the European Guide recommendation, the results were bad. Furthermore, other researchers [5, 6], obtained great fresh state properties of SCC based on the same method. This results show the importance of the component materials in terms of quality, chemical and physical composition. Nevertheless, it is important to verify the fresh properties for every designed mix because of the variety of affecting factors, every single mix is unique. For the mixes 1 and 3, the deformability requirement was not satisfied, with a flow diameter below the recommended values. In terms of stability, bleeding and segregation occurs in the mixes 2, 4, 5 and 6 because of the high water/binder ratio. The final composition (Figure 2) exhibited the characteristics of a SCC concrete, according to the European Guideline [2], with a SF1 640 mm flow diameter, a flow time that indicates a good viscosity as expressed by the VS2 and VF2 indications, and adequate PL2 passing ability with no blockage between the bars.

4.2 Compressive strength

The compressive strength at 28 days, $f_{cm,}$ for the SCC with fly ash addition (Mix 7) was 45 MPa, equivalent for the designed concrete class C35/45. The maximum loads and the compressive strength for all the concrete mixes are presented in Table 3.

Table 3: Compressive strength of the concrete mixes

Mix	Code	Maximum load (kN)	Dimensions (mm)	fcm (MPa)	Mean fcm (MPa)	Strength class
Mix 7 -SCC	7R	1037.20	150x150x150	46	45.7	C35/45
	7S	1013.40	150x150x150	45		
	7T	1025.50	150x150x150	46		
Mix 1 -Conventional concrete	1A	1012.90	142x142x142	50	50.5	C40/50
	1B	1027.70	142x142x142	51		
Mix 2 -Conventional concrete	2A	687.50	142x142x142	34	34.5	C25/30
	2B	715.20	142x142x142	35		
Mix 3 -Conventional concrete	3A	550.00	142x142x142	27	26.5	C20/25
	3B	528.00	142x142x142	26		
Mix 4 -Conventional concrete	4A	734.20	142x142x142	36	38.0	C30/37
	4B	802.80	142x142x142	40		
Mix 5 -Conventional concrete	5A	604.30	142x142x142	30	28.5	C20/25
	5B	534.40	142x142x142	27		
Mix 6 -Conventional concrete	6A	642.80	142x142x142	32	31.5	C25/30
	6B	628.50	142x142x142	31		
Mix 7 -SCC	7A	899.90	142x142x142	45	45.0	C35/45
	7B	905.80	142x142x142	45		

Mix 7 was tested in both 142 mm cubes and 150 mm cubes. A relationship which takes into account the size of the testing samples can be detailed as follows: $f_{cm,150mm\ cube} = 0.985*f_{cm,140mm\ cube}$. If applied to all the mixes, the concrete class can be seen in the last column of Table 3.
A comparative graphic with the compressive strength of the concrete mixes is shown in Figure 3. The water/binder ratio is one of the most important factors which affect the compressive strength and, as confirmed by previous research [7-9], the strength increases with the decrease of the water addition (Figure 4).

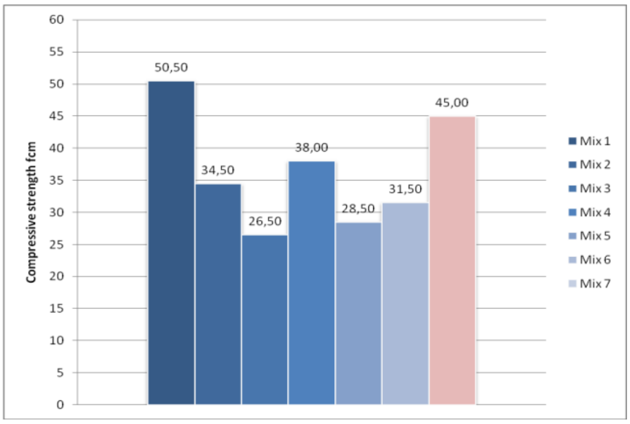

Figure 3. Compressive strength of the concrete mixes.

Furthermore, the water amount affects the concrete porosity. A high water/binder ratio increases the porosity and reduces the density of concrete. Regarding the fly ash percentage, there is no relevant relationship between that and the compressive strength at 28 days (Figure 5).

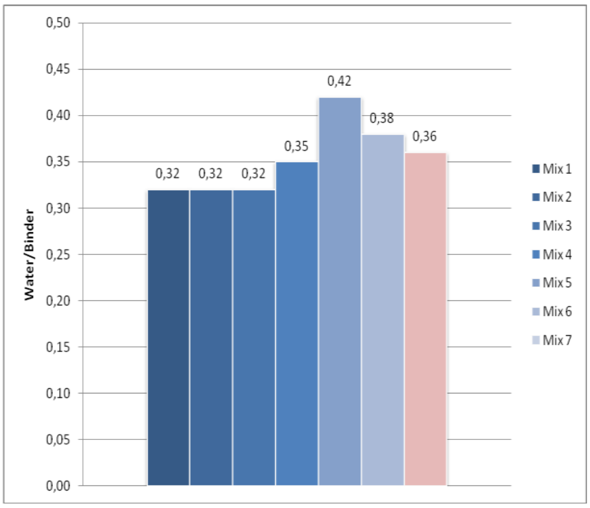

Figure 4. Water/binder ratio

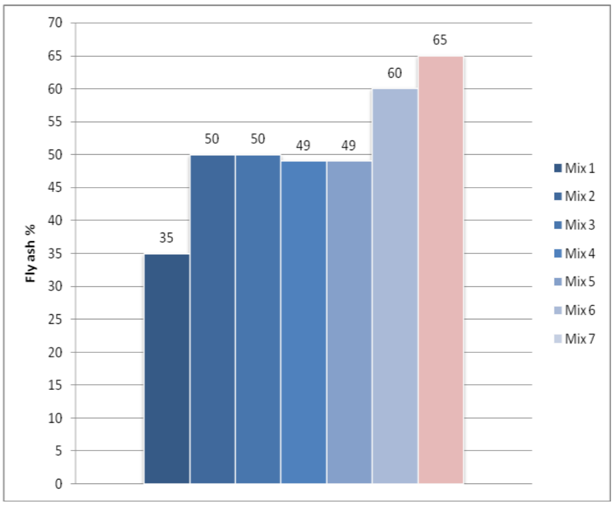

Figure 5. Fly ash substitution of cement

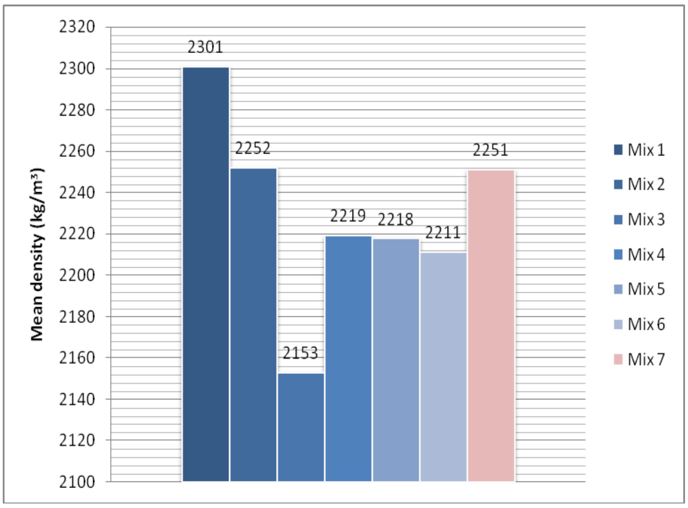

Figure 6. Density of the concrete mixes.

Relating the density of concrete with the 28 days compressive strength, we can see a directly proportional relationship, as is shown in the Figure 6. High density means low porosity, using the same constituents in the mixes, which leads to higher compressive strength of the specimens. Analyzing the density of all seven mixes, we can conclude that the density is affected by the compaction grade of the concrete.

4.2 Chloride penetration

The total charge passed through the specimen in RCPT during a period of 6 Hours is 7789, Coulomb. A value higher than 4000 Coulomb, classifies to high chloride ion penetrability according to ASSTM C1202. At 28 days, SCC with fly ash addition shows very low resistance to chloride penetration. That could be caused by the delayed pozzolanic reaction of fly ash, which usually is considered at 56 days. Bad results at the age of 28 days, are obtained in other studies too [11], but after the age of 15 weeks, the chloride penetration is reduced.[12]

After the 7 days exposure in chloride solution, the maximum penetration depth of the immersed specimens was 9 mm. The reference specimen (7F) was cured in water until the testing day and exhibited no chloride penetration as it is showed in Figure 7. However, the exposure solution is quite aggressive, due to the high concentration of the chloride solution. This combined with the early age of testing (35 days) for a high volume fly ash concrete, render a quite low chloride penetration depth. As a consequence, further tests are in need to clarify the problem and the experimental program will be continued with the influence of the testing age on the durability behavior of SCC.

Figure 7. Chloride penetration depth

4.3 Sulfate resistance

The compressive strength of the SCC specimens, after the 7 days immersion in magnesium sulfate solution, is lower with 3.98% than the reference samples cured in water until age of 35 days. The insignificant loss of strength indicates a good sulfate resistance for short periods of time, in spite of the high concentration of the sulfate solution.

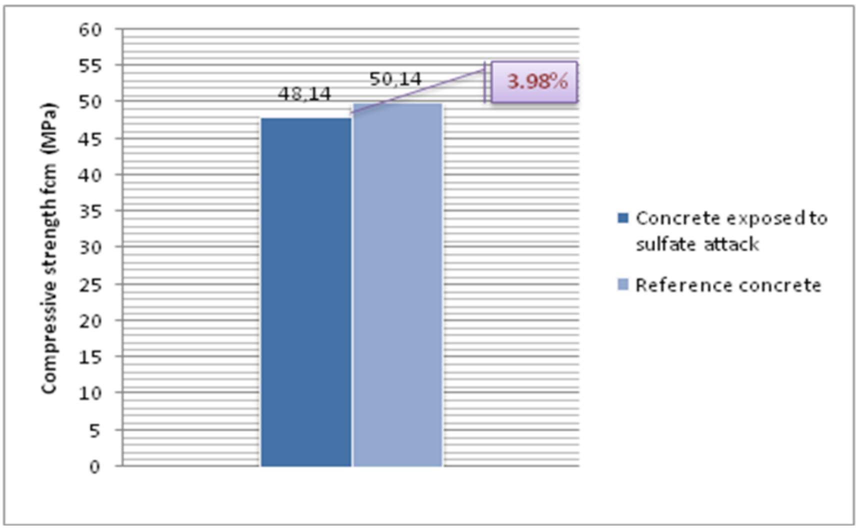

Figure 8. Loss of compressive strength due to the sulfate attack.

The most common experimental sulfate attack is the exposure to sodium sulfate [14], but the magnesium sulfate is more aggressive. Analyzing the specimen surfaces we can observe some harmful coloration specific for the sulfate attack. The testing age is quite early because of the late reaction of fly ash. Therefore, a long term sulfate resistance study will be continued. The compressive strength for the SCC exposed to sulfate attack and the reference SCC is showed in Figure 8.

4.4 Carbonation

The carbonation depth after 20 days of exposure to a high CO_2 concentration is maximum 2 mm. The reference samples, cured in water until the testing day, indicated no carbonation tendency. The carbonation depths for the specimens exposed and for the reference concrete are showed in Figure 9. Commonly, when in an experimental study, carbonation is studied for a longer period of time, 4 years [16] or 10 years [17], the results are more realistic.

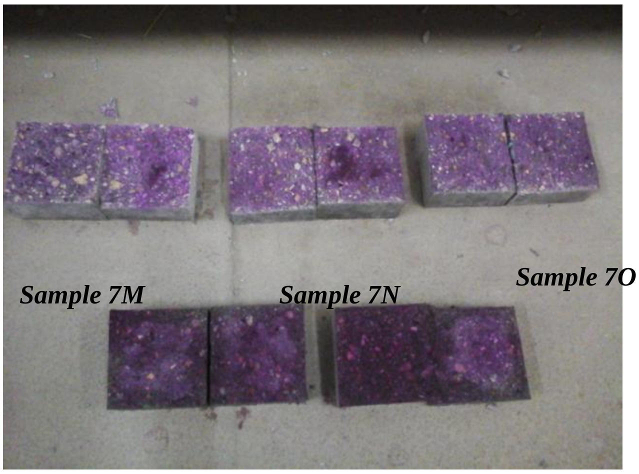

Figure 9. Carbonation depth.

5. Conclusions

This experimental program describes the effect of fly ash on the workability, strength and durability of self compacting concrete. There are promising results in all studied aspects, but more research is necessary to establish the long term effect of fly ash. The main purpose of this experiment was to obtain a low cost, high performance self compacting concrete with high volume fly ash. That was possible with a substitution of 65% fly ash of the cement amount, a water/binder ratio of 0.36 and a cement content of 370 kg/m^3. The fly ash addition improved the workability and reduced the HRWA. Furthermore, it had a beneficial contribution on the cohesion and segregation resistance. The compressive strength at 28 days reached 45.6 MPa. As we expected, the compressive strength increased with the increase of density and the reduction of water/binder ratio. Due to the early testing age for a high volume fly ash concrete, the rapid chloride permeability test indicates low resistances to chloride, whereas the results obtained with the exposure to a concentrated chloride solution are more encouraging. The sulfate resistance is improved with the addition of fly ash because of the negligible loss of strength after the magnesium sulfate exposure. Carbonation depth is up to 2 mm, but due to uncontrolled test environment, the test results are conservative and will be further studied.

6. References

[1] P. Taylor ,P. Tennis, K. Obla, P. Ram, T. Van Dam, H. Dylla. *Durability of Concrete.* 2nd edition, Transportation Research Circular. Washington, 2013

[2] ACI Commitee 226. Use of Fly Ash in Concrete. *ACI Materials Journal*, September- October pp. 381-409, 1987

[3] L. Mlinarik, K. Kopecsko. Impact of metakaolin - a new supplementary material – on the hydratation mechanism of cements. *Acta Tehnica Napocensis: Civil Engineering & Architecture.* **Vol. 56**, pp 100-110, 2013

[4] European Project Group. *The European Guidelines for Self Compacting Concrete*. *Specification production and use*, 2005

[5] M. Gheorghe, N. Saca, C. Ghecef, R. Pintoi, L.Radu. Beton autocompactant cu cenușă zburătoare. *Revista Română de Materiale* , **Vol. 41**, pp 201-210, 2011.

[6] M. Lachemi, K. Hossain, V. Lambros, N.Bouzoubaa. Development of Cost-Effective self-Consolidating Concrete Incorporating Fly Ash, slag Cement, or Viscosity-Modifying Admixtures. *ACI Materials Journal*, **Vol. 100**, pp 419-425, 2003.

[7] T.Eck. Research for Durable Concrete with Fly Ash. *International RILEM Conference on Material Science*, **Vol. 3**, pp 45-55, 2010.

[8] M.Akram Tahir, *Strength Develeopment of Concrete due to Chemical Composition of Incorporate Fly Ash*, 30th Conference on Our World in Concrete & Structures, Singapore, 2005

[9] A. Bilodeau, M. Malhotra, High-Volume fly Ash System: Concrete Solution for Sustainable Development, *ACI Materials Journal*, **Vol. 97**, pp 41-47, 2000.

[10] L.Tang, W.Zhu. Chloride Penetration. Durability of Self-Compacting Concrete *State-of-the-Art Report of RILEM Technical Committee 205-DSC*, 2007.

[11] Z.Yu, G.Ye. *Chloride Penetration and Microstructure Development of Fly Ash Concrete*, Second International Conference on Microstructural-Related Durability of Cementtious Composites, Amsterdam, 2012.

[12] Z. Li, J. Peng, B. Ma. Investigation of Chloride Diffusion for High-Performance Concrete Containing Fly Ash, Microsilica and Chemical Admixtures, *ACI Materials Journal*, **Vol. 96**, pp 391-396, 1999.

[13] M. Santhanam. *Sulphate Attack from an Engineering Persperctive*, RILEM Workshop on Performance of Cement-Based Materials in Aggressive Aqueous Environments. Belgium, 2008.

[14] P. Tikalsky, R. Carrasquilo. Infleunce of Fly Ash on the Sulfate Resistance of Concrete, *ACI Materials Journal*, **Vol. 89**, pp 69-75, 1992.

[15] K. Audenaert. Carbonation- Durability of Self-Compacting Concrete. *State-of-the-Art Report of RILEM Technical Committee 205-DSC*, 2007.

[16] M. Haque, M. Kawamura. Carbonation and Chloride-Induced Corrosin of Reinforcement in Fly Ash Concretes, *ACI Materials Journal*, **Vol. 89**, pp 41-48, 1992.

[17] M. Malhotra, M. Zhang, P. Read, J. Ryell. Long- Term Mechanical Properties and Durability Characteristics of High-Strength/High-Performance Concrete incorporating Supplementary Cementing Materials unde Outdoor exposure Conditions. *ACI Materials Journal*. **Vol. 97,** pp 518-525**,** 2000.

[18] *Specificație tehnică privind producerea betonului autocompactant*- Anteproiect, 2012