PROPERTIES OF HIGH-VOLUME FLY ASH CONCRETE AND ITS ROLE IN SUSTAINABLE DEVELOPMENT

Jelena Dragaš[1]
Snežana Marinković[2]
Ivan Ignjatović[3]
Nikola Tošić[4]

UDK: 666.973.2:502.17
DOI: 10.14415/konferencijaGFS2014.115

Summary: *Sustainability is important to the well-being of our planet, continued growth of a society and human development. Concrete is the most widely used construction material in the world. For a variety of reasons, the concrete construction industry is not sustainable: it consumes huge quantities of virgin materials, the production of Portland cement is a major contributor to greenhouse gas emissions, and many concrete structures suffer from lack of durability. Recent research has led to the point where numerous by-products of industrial processes with pozzolanic properties can be substituted partially for cement. One of the most widely used pozzolanic materials in concrete is fly ash – a by-product of burning ground coal in power plants. Addition of fly ash to concrete and replacement of cement up to 30 % can improve workability, porosity and durability. As a result, fly ash content up to 30 % in cement has become generally accepted. In this paper, a brief review of the published research on the properties of concrete containing from 30 % to 70 % replacement of cement with fly ash – so called high-volume fly ash concrete - is presented. Mechanisms are discussed by which the incorporation of high volume of fly ash in concrete reduces the water demand, improves the workability and enhances durability.*

Keywords: *High volume fly ash concrete, Mechanical properties, Durability, Cement*

1. INTRODUCTION

Human activities represent a serious threat to the environment and among them the building industry has one of the largest environmental impacts. Concrete is the world's

[1] Jelena Dragaš, dipl.inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 618, e – mail: jelenad@imk.grf.bg.ac.rs
[2] Prof. dr Snežana Marinković, dipl.inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: ++381 11 3218 547, e – mail: sneska@imk.grf.bg.ac.rs
[3] dr Ivan Ignjatović, dipl.inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 546, e – mail: ivani@imk.grf.bg.ac.rs
[4] Nikola Tošić, dipl.inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 501, e – mail: ntosic@imk.grf.bg.ac.rs

most consumed man-made material. Unfortunately, the production of Portland cement, the active ingredient in concrete, generates a significant amount of carbon dioxide (CO_2). During the production of Portland cement, carbon dioxide (CO_2) is released due to the combustion of carbon-based fuels and the calcination of limestone [1]. For each ton of Portland cement clinker that is produced, approximately one ton of the greenhouse gas CO_2 is released [2]. With cement production reaching nearly 6 billion tons per year worldwide, the sustainability of concrete is a very real concern.
A reduction in CO_2 emissions may be achieved by reducing the demand for Portland cement with the use of pozzolanic materials in concrete, as a partial replacement of cement. Fly ash is most commonly used as a supplementary cementitious material (SCM) in the production of Portland cement concrete. Fly ash is an inorganic, non-combustible by-product of coal-burning power plants. As coal is burnt at high temperatures, carbon is burnt off and most of the mineral impurities are carried away by the flue gas in the form of ash.
The molten ash is cooled rapidly and solidifies as spherical, glassy particles [3]. Fly ash particles range in diameter from less than 1 micron up to 150 microns [4]. Despite modernization efforts in many countries, the main energy source globally still remains coal combustion. As a result, large amounts of fly ash are being generated worldwide. In Serbia, there are six coal-burning power plants which cover about 70% of the country's electric energy needs [5]. During 2010, about 40 million tons of coal was exploited and transported from "Kolubara" and "Kostolac" mines. But these processes have a major environmental consequence – 6 million tons of fly ash obtained per year, mostly produced in "Nikola Tesla A" and "Nikola Tesla B" power plants located about 30 km away from Belgrade, the city with 2 million people and the capital of Serbia.
In Serbia, about 200 million tons of fly ash is being currently deposited at surface area of 1.500 hectares. Fly ash landfills are located next to power plants and they cover a significant part of the arable land. In power plant "Nikola Tesla B", during the 2009/2010 repair, the new system of collection, transport and disposal of fly ash was established. Applying new technology enabled collecting of dry fly ash in silos and its delivery for the industrial needs afterwards. But, at the moment, only 2.7% of the total fly ash production in Serbia is used by the construction industry. There is an ongoing question about whether fly ash is a hazardous waste or not. A lot of speculations about the answer to that question are the obstacle to bigger commercial use of fly ash in constructions. In February 2014, United States Environmental Protection Agency released a report [6] concluding that environmental releases of constituents of potential concern from fly ash concrete during use is comparable to or lower than concrete without fly ash, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors. This should be stimulation for greater future use of fly ash in concrete production.

2. HIGH VOLUME FLY ASH CONCRETE - HVFAC

Most fly ash is pozzolanic, which means it's a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties. In the presence of moisture, alumino-silicates within the fly ash react with calcium ions to form calcium silicate hydrates [4]. The hydrated silicate develops strength and the lime fills the voids. Properly selected fly ash reacts with the lime to form CSH–the same cementing product as in Portland cement.

This reaction of fly ash with lime in concrete improves strength. Pozzolanic reaction occurs at a slow rate and releases little heat of hydration in comparison to the cementitious reactions. ASTM C618 [7] classifies fly ash as Class C or F. It is true that the specification states that Class F ashes are mainly produced from bituminous or anthracite coals and that Class C ashes are mainly produced from sub-bituminous or lignite coals, but the main criterion for classification are its chemical requirements: $SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$ for Class F and $SiO_2 + Al_2O_3 + Fe2O_3 > 50\%$ for Class C. Usually, Class F fly ashes have a low content of CaO and exhibit pozzolanic properties, but Class C fly ashes contain more than 12% of CaO and exhibit cementitious properties. Fly ash from six power plants in Serbia is classified as class F. Since the 1930’s, fly ash has been used as a partial replacement of Portland cement in concrete to improve the material’s strength and durability, while also limiting the amount of early heat generation.

Traditional specifications limit the amount of fly ash to 25% or 30% cement replacement. Today, there is a general trend to replace higher contents of Portland cement with fly ash in concrete. The increased pressure to use higher content of fly ash in concrete comes from three main aspects. The first aspect is economics. In most markets fly ash is less expensive than Portland cement. Therefore, as the replacement level of fly ash increases, the cost of the concrete production decreases.

The second aspect and arguably the most important is the environment. Replacing cement with fly ash reduces concrete’s overall carbon footprint and diverts an industrial by-product from the solid waste stream. The third aspect influencing the use of higher replacement levels is the technical benefits of high volume fly ash concrete (HVFAC). HVFAC has improved performance over ordinary Portland cement concrete, especially in terms of durability when appropriately used. HVFAC is defined as concrete containing more than 30% fly ash by mass of total cement material. The HVFAC has good workability, low heat of hydration, low drying shrinkage and good durability [8]. But, at all replacement rates, fly ash generally slows down the setting time and hardening rates of concrete at early ages, especially under cold weather conditions, and when less reactive fly ashes are used. Furthermore, with industrial by-products, some variability in physical and chemical characteristics will normally occur, not only between power plants but also within the same plant. However, when properly designed, HVFAC can have adequate early-age strength and high later-age strength.

Therefore, to achieve the benefits of HVFAC, guidelines are needed for its proper application in structural concrete.The fly ash concrete mix techniques can generally be divided into three main categories: Addition method which involves direct weight addition of fly ash to cement, replacing part of the aggregate in concrete; Simple replacement method which involves direct weight replacement of a part of Portland cement with fly ash and Partial replacement method which involves replacement of a part of the Portland cement with excess weight of fly ash, replacing also part of the aggregate.

3. PROPERTIES OF FRESH AND HARDENED HVFAC

3.1. Water-to-Cementitious Materials Ratio

The water-cement (w/c) ratio is defined as the mass of water divided by the mass of cement. Similarly, the water-cementitious material (w/cm) ratio is defined as the mass of water divided by the mass of all cementitious materials (cement plus fly ash). When proportioning HVFAC, a low w/cm ratio is necessary. During research conducted at CANMET, Bilodeau [8] determined that for HVFAC, the proportion of fly ash should be as high as possible and the w/cm ratio as low as possible to provide adequate early age strength and durability. The literature showed that other studies utilized w/cm ratio in the range of 0.19 to 0.60 in most cases. According to Malhotra [8], to insure proper performance w/cm ratio should be kept as low as possible, preferably below 0.40.

3.2. Setting Time

Mehta and Monteiro [10] define setting of concrete as “the onset of solidification in a fresh concrete mixture.” Initial setting time defines the time at which fresh concrete can no longer be properly mixed and placed, whereas final setting time defines the beginning of the development of mechanical properties. Setting time for HVFAC is influenced by the following factors: class and quantity of fly ash, type and quantity of cement, concrete temperature, use of chemical admixtures, and w/cm ratio [10]. Ravina and Mehta [11] indicates that HVFAC exhibit delayed setting times when compared to a control mixture with no fly ash replacement and a similar w/cm ratio. This research [11] reported initial setting time delays of 20 minutes to 4 hours and 20 minutes and final setting time delays of 1 hour to 5 hours and 15 minutes when compared to the control concrete depending on the fly ash type and dosage. ASTM Class C fly ashes resulted in longer setting times when compared to equivalent concrete mixtures prepared with Class F fly ashes. Also, the delay in setting times increased with higher fly ash replacement levels.

3.3. Chemical Admixtures

High range water-reducing admixtures are typically required to maintain adequate workability at low w/cm ratios. Naphtaline-based, sulfonated naphthaline-formaldehyde and polycarboxylic ether based superplasticizer are mostly used to achive the required workability. Having in mind the slow setting time of HVFAC, accelerating admixtures are often used to shorten the set times by increasing the rate of hydration. With the correct accelerator dosage, setting times and early-age strength development for HVFAC can be made comparable to conventional concrete.

3.4. Workability and Water Demand

The use of fly ash as cement replacement generally reduces the water demand for a given workability. Thomas [12] approximates that each 10% of fly ash replacement should provide at least 3% water reduction. Mehta [13] states that the reductions in water demand may be attributed to three mechanisms. First, the fine fly ash particles prevent cement flocculation. Also, since the fly ash particles have a smooth, spherical surface, interparticle friction is reduced. Finally, the reduction in water demand may be attributed to more efficient particle packing within the paste. Based on the results, it is apparent that fly ash may be used as a water reducing SCM at high replacement levels.

3.5. Bleeding

Gebler and Klieger [14] verified that fly ash reduces the bleeding capacity of concrete. They also found that concretes proportioned with Class C ashes generally exhibited less bleed water than those proportioned with Class F ashes. The bleeding capacity of a concrete mixture is directly related to the water demand. Therefore, bleeding is typically reduced in HVFAC mixtures due to the low water contents required for adequate workability.

3.6. Heat of Hydration

Hydration of cement is an exothermic process. When fly ash is used to replace cement in Portland cement concrete, the rate of heat development and overall heat of hydration is altered. In some cases, the total heat of hydration is reduced, which can be very beneficial in mass concrete construction. Langley [15] performed research to quantify the effect that high fly ash dosages have on the temperature rise for concrete. The research showed that the temperature rise caused by the hydration of HVFAC may be significantly reduced.

3.7. Strength

The rate of strength gain in mixtures containing high volumes of fly ash will be slower due to the slow rate of the pozzolanic reaction.
This results in lower early strengths. However, the pozzolanic reaction will also generally produce greater strengths at later ages. Both the strength at a given age and the rate of strength gain of fly ash concrete are affected by the characteristics of the fly ash, the type of cement, the proportions of each used in the concrete mix and w/cm ratio [16]. Fig. 1, 2 and 3 show relationship between compressive strenght of concrete made with fly ash compared to referent concrete (cement concrete with the cement content equal to cementitious materials content of fly ash concrete) and procentage of replacement of cement with fly ash.
Compressive strenghts of specimens are measured at the age of 7, 28 and 91 days, respectively. All specimens had w/cm ratio from 0.40 to 0.60 and the total cementitious content from 400 to 415kg/m^3 of concrete. T
he replacement of cement varied from 15 to 70 percent of total cementitious materials mass. It can be concluded that increase of cement replacement leads to decrease of compressive strenght of concrete at all ages. Fig. 4 shows compressive strenght growth of concrete made with 228kg/m^3 of fly ash and 186kg/m^3 of cement and w/cm ratio of 0.38, 0.43 and 0.50 [17]. It can be concluded that w/cm ratio is a very important factor of influence on compressive strenght of HVFAC. To achieve good early and long term strenght of HVFAC w/cm should be as low as possible.

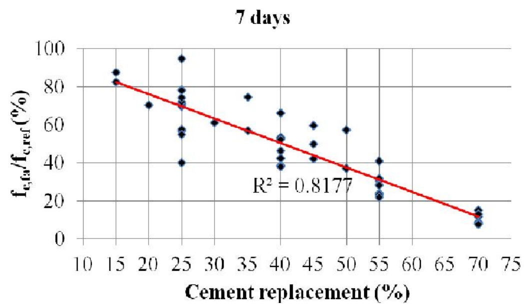

Figure 1. Compressive strenght of fly ash concrete/compressive strenght of cement concrete ratio at the age of 7 days depending on the cement replacement [17, 18, 19, 20, 21]

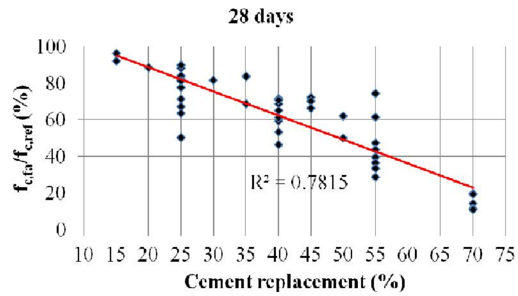

Figure 2. Compressive strenght of fly ash concrete/compressive strenght of cement concrete ratio at the age of 28 days depending on the cement replacement [17, 18, 19, 20, 21, 22]

Results shown in Fig. 1, 2 and 3 indicate that compressive strenght of fly ash concrete with cement replacement from 30 % to 70 % and w/cm ratio above 0.40 is lower than that

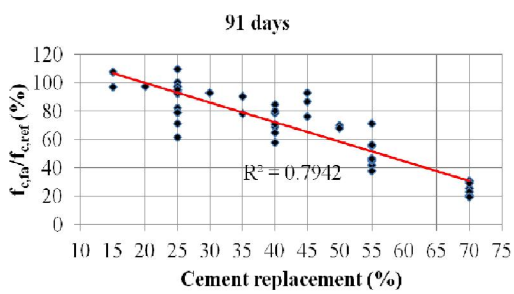

Figure 3. Compressive strenght of fly ash concrete/compressive strenght of cement concrete ratio at the age of 91 days depending on the cement replacement [17, 18, 19, 20, 21]

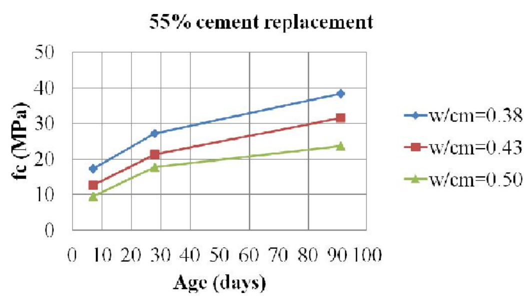

Figure 4. Compressive strenght growth of fly ash concrete with 55% replacement of cement depending on the w/cm ratio [17]

of referent cement concrete even after 91 days. However, lowering the w/cm ratio below 0.40 and/or replacing not only the part of the cement but also the part of fine aggregate with fly ash can significantly improve the HVFAC compressive strength at all ages [8, 23, 24].

Results from [23] indicate that HVFAC with 50% of cement replacement and w/cm ratio of 0.30 can achieve equal compressive strenght as that of referent cement concrete at the age of 28 days.

The HVFAC strength at the age of 3 days was decreased by 25% compared to the referent concrete strength, but still adequate for practical use in concrete construction.

Research from [24] investigated HVFAC with 45% of cement replacement and w/cm ratio of 0.34, but the total fly ash mass was larger than mass of cement replacement. Concrete mixture was made with 211.75kg/m^3 of cement and 278.25kg/m^3 of fly ash. Results showed that 3-day compressive strenght was 91% and 14-days compressive strenght was 94% of referent cement concrete strength with 385kg/m^3 of cement.

3.8. Durability

One of the major advantages of use of fly ash in concrete mixes is an improved durability of concrete. The existance of large pores and crystalline products in the transition zone in concrete without fly ash are greatly reduced by the the introduction of fly ash particles.

The decrease in water content and fine fly ash particles decreases the permeability of fly ash concrete. The reduced permability results in improved long term durability and resistance to various deterioration processes of concrete structures.

Acording to Bilodeau and Malhotra [25] HVFAC has exellent resistance to repeated cycles of freezing and thawing and very high resistance to the penetration of chloride ions. This resistance was considerably higher than that of conventional Portland cement concrete of similar strength [25].

The freeze-thaw resistance of concrete in the presence of deicing salts is generally lower than the resistance to freezing and thawing alone. Laboratory tests have demonstrated that HVFAC can provide an excellent protection to the reinforcing steel against corrosion.

A study performed at CANMET [25] on the sulfate resistance of concrete specimens immersed in a 5% Na_2SO_4 solution demonstrated that the HVFAC performed better than the reference cement concrete without fly ash. Alkali-aggregate reaction is caused by the expansion of concrete due to the reaction between the cement alkalies and certain types of reactive silica in aggregates [25]. Extensive tests performed at CANMET [25] showed that the use of HVFAC can effectively reduce the expansion due to alkali-silica reaction.

4. CONCLUSION

The effects of high fly ash dosage on selected fresh and hardened concrete properties may be summarized as follows:

- The use of fly ash generally reduces the water demand for a given workability,
- Bleeding is typically reduced for HVFACs mixtures due to low water contents,
- HVFAC exhibit delayed setting times when compared to a referent concrete with no fly ash replacement,
- Most of the test results show that HVFACs with simple replacement of cement don’t have compressive strenght comparable to concrete without fly ash. However, concrete mixtures with w/cm ratio below 0.4 and/or amount of fly ash that is grater then the amount of removed cement can achieve compressive strenghts equal to or comparable to concrete without fly ash at all ages. Adequate workability of HVFAC

with low w/cm ratio can be easily achieved with the addition of high range water-reducing admixtures.

ACKNOWLEDGEMENTS

The work reported in this study is a part of the investigation within the Research Project TR36017: 'Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible applications', supported by the Ministry for Education, Science and Technology, Republic of Serbia This support is gratefully acknowledged.

REFERENCES

[1] Chen, I.A., and M.C.G. Juenger. Incorporation of Waste Materials into Portland Cement Clinker Synthesized from Natural Raw Materials. *Journal of Materials Science,* 2009, 44, no. 10:2617-2627.

[2] Greer, W. L., G. J. Hawkins, and T. B. Carter. Air Emissions and Control Measures. Chap. 6.1 in *Innovations in Portland Cement Manufacturing*. Skokie, 2004, Illinois: Portland Cement Association.

[3] Malhotra, V.M. and P.K. Mehta. High Performance, High-Volume Fly Ash Concrete. Supplementary Cementing Materials for Sustainable Development, Inc., Ottawa, Canada, 2002, 101 pages.

[4] Malhotra, V.M., and Ramezanianpour, A.A., *Fly Ash in Concrete, Second Edition,* Natural Resources Canada, Ottawa, Ontario, 1994, CANMET – Canadian Centre for Mineral and Energy Technology.

[5] Годишњи извештај Електропривреде Србије 2011 (http://www.eps.rs/GodisnjiIzvestaji/ Godisnjak%20EPS%202011_sr_web.pdf), При- ступљено 29. августа 2013.

[6] United States Environmental Protection Agency, Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard-Final report, February 2014.

[7] ASTM C618-12a: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, 2012.

[8] Malhotra, V.M., High-Performance high-volume fly ash concrete, Concrete International, 2002, 30-34.

[9] Bilodeau, A., V.M. Malhotra, and P.T. Seabrook., Use of High-Volume Fly Ash Concrete at the Liu Centre. International Centre for Sustainable Development of Cement and Concrete (ICON), Materials and Research Laboratory, CANMET. Natural Resources Canada. Ottawa, Canada, 2001, 21 pages.

[10] Mehta, K. and P. Monteiro., *Concrete: Microstructure, Properties and Materials*. 3d. ed. New York: McGraw Hill, 2006.

[11] Ravina, D, and P.K. Mehta., Properties of Fresh Concrete Containing Large Amounts of Fly Ash. *Cement and Concrete Research*, 1986, Vol. 16, No. 6, 227-238.

[12] Thomas, M., *Optimizing the Use of Fly Ash in Concrete*. Portland Cement Association, 2007, Skokie, IL. 24 pages.

[13] Mehta, P. K., High-Performance, High-Volume Fly Ash Concrete for Sustainable Development, *Proceedings of the International Workshop on Sustainable Development and Concrete Technology*. ed. Kejin Wang., 2004, 3-14. Center for Transportation Research and Education, Iowa State University.

[14] Gebler, S.H., and P. Klieger., Effect of Fly Ash on the Durability of Air-Entrained Concrete. *Proceedings of the 2nd International Conference on Fly Ash, Silica Fume, Slag, and other Natural Pozzolans in Concrete*. ACI SP-91, Vol.1, American Concrete Institute, Farmington Hills, MI, 1986, 483-519.

[15] Langley, W.S., G.G. Carette, and V.M. Malhotra., Strength Development and Temperature Rise in Large Concrete Blocks Containing High Volumes of Low-Calcium (ASTM Class F) Fly Ash. *ACI Materials Journal*, 1992, Vol. 89, No. 4, 362-368.

[16] Berry, E.E., and Malhotra, V.M., “Fly Ash in Concrete”. Energy, Mines and Resources Canada, CANMET, Ottawa, Canada, 1986.

[17] Quan Hongzhu and Kasami Hideo, Experimental Study on Effects of Type and Replacement Ratio of Fly Ash on Strength and Durability of Concrete, *The Open Civil Engineering Journal*, 2013, Vol. 7, 93-100.

[18] Lam L., Wong Y.L., Poon Chi-Sun, Effect of fly ash and silica fume on compressive and fracture behaviors of concrete, *Cement and Concrete Research*, 1988, Vol. 8, 271–283.

[19] Siddique Rafat, Performance characteristics of high-volume Class F fly ash concrete, *Cement and Concrete Research*, 2004, Vol. 34, 487-493.

[20] Mittal Amit, Kaisere M.B., Shetti Rajendrakuma, Experimantal study on use of fly ash in concrete, *Tarapur Atomic Power Project 3 and 4*, Nuclear Power Corporation of India, 2006.

[21] Kou Shi-Cong, Poon Chi-Sun, Chan Dixon, Influence of Fly Ash as Cement Replacement on the Properties of Recycled Aggregate Concrete, *Journal of materials in civil engineering*, 2007,Vol. 19, 709-717.

[22] Kou Shi-Cong, Poon Chi-Sun, Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash, *Cement and Concrete Composites*, 2013, Vol. 37, 12-19.

[23] Atis Cengiz Duran, High-Volume Fly Ash Concrete with High Strength and Low Drying Shrinkage, Journal of materials in civil engineering, 2003, Vol. 5, 153-156.

[24] McCarthy M.J. and Dhir R.K., Development of high volume fly ash cements for use in concrete construction, Fuel, 2005, Vol. 84, 1423–1432.

[25] Alain Bilodeau and V. Mohan Malhotra, High-Volume Fly ash System: Concrete Solution for Sustainable Development, ACI Materials Journal, 2000, Vol. 97, 41-47.

КАРАКТЕРИСТИКЕ БЕТОНА СА ВИСОКИМ САДРЖАЈЕМ ЛЕТЕЋЕГ ПЕПЕЛА, И ЊЕГОВА УЛОГА У ОДРЖИВОМ РАЗВОЈУ

Резиме: *Одрживост је принцип који је од великог значаја за будућност Земље и развој човечанства. Бетон је грађевински материјал који се у свету користи у највећим количинама. Много је разлога због којих индустрија бетона није у складу са одрживим развојем: користи велике количине природних материјала, производња портланд цемента значајно учествује у укупној емисији угљен-диоксида у атмосферу, већина бетона има ограничену трајност. Досадашња истраживања су допринела коришћењу различитих нус продуката разних индустрија која имају пуцоланска својства као делимичне замене за цемент. Један од најчешће коришћених нус продуката је летећи пепео - отпад који настаје сагоревањем угља у термоелектранама. Додатак летећег пепела бетону и замена цемента летећим пепелом до 30% доприноси бољој уградљивости, мањој порозности и већој трајности. У овом раду је дат је кратак преглед литературе о бетонима који садрже летећи пепео као 30% до 70% замене цемента – бетони са високим садржајем летећег пепела. Разматрани су механизми у бетонима са летећим пепелом који доводе до смањења потребне воде, повећања уградљивости и трајности.*

Кључне речи: *Бетони са високим садржајем летећег пепела, теханичке карактеристике, трајност, цемент*