MOGUĆNOSTI PRIBLIŽAVANJA BETONSKE INDUSTRIJE CIRKULARNOM MODELU KROZ INDUSTRIJSKU SIMBIOZU

POSSIBILITIES IN CONCRETE INDUSTRY TOWARDS CIRCULAR ECONOMY THROUGH INDUSTRIAL SYMBIOSIS

Dubravka BJEGOVIĆ
Marijana SERDAR
Marija JELČIĆ RUKAVINA
Ana BARIČEVIĆ
Martina PEZER

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1 UVOD

U skladu s porastom globalizacije i industrijalizacije, širom svijeta rastu i zahtjevi za čistim okolišem, očuvanjem izvora energije i zbrinjavanjem otpada. Zaštita okoliša i ušteda energije postaju ključni svjetski problemi u svim poljima tehnologije. Da bi se produžilo postojanje čistog okoliša, javlja se potreba za unaprjeđivanjem postojećih tehnologija, pretvarajući ih u održive i ekološki savjesne. Pojam održivosti 1992. godine na EarthSummitu u Rio de Janeiru definiran je kao gospodarstvena djelatnost koja je u skladu sa zemljinim ekosustavom [1]. Osnovni princip održivog razvoja je korištenje što manje prirodnih resursa i stvaranje što manje po Zemlju štetnih otpada.

Tradicionalna betonska industrija još uvijek se bazira na linearnom modelu, u kojem se za potrebe proizvodnje betona koristi velika količina prirodnih neobnovljivih resursa, emitira velika količina stakleničkih plinova, te proizvede velika količina otpada. Godišnje se u Europi

1 INTRODUCTION

Environmental protection and energy saving are crucial problems in all fields of human activities, especially in production and industry. Sustainable development has become one of the most evident solutions in order to prolong the existence of clean and healthy environment. The 1992 Earth Summit in Rio de Janeiro defined sustainable development as economic activity that is in harmony with the earth's ecosystem [1]. The best way to ensure sustainable development would be to reconcile human needs with the capacity of the planet to cope with the consequences of human activities, or, in other words, to take from the earth as little as possible natural resources and return to the earth as little as possible waste.

Traditional concrete industry is based on linear model, in which during production of concrete elements a large amount of non-renewable resources is utilised and significant air emissions caused, and at the end of the service life energy is used for demolition of structure

Prof. dr. sc. Dubravka Bjegović, redoviti profesor, Zavod za materijale, Građevinski fakultet Sveučilišta u Zagrebu, Zagreb, Hrvatska

Dr. sc. Marijana Serdar, viši asistent znanstveni novak, Zavod za materijale, Građevinski fakultet Sveučilišta u Zagrebu, Zagreb, Hrvatska

Dr. sc. Marija Jelčić Rukavina, asistent znanstveni novak, Zavod za materijale, Građevinski fakultet Sveučilišta u Zagrebu, Zagreb, Hrvatska

Ana Baričević, asistent znanstveni novak, Zavod za materijale, Građevinski fakultet Sveučilišta u Zagrebu, Zagreb, Hrvatska

Martina Pezer, stručni suradnik, Zavod za materijale, Građevinski fakultet Sveučilišta u Zagrebu, Zagreb, Hrvatska

Dubravka Bjegovic, PhD, Professor, Department of materials, Faculty of Civil Engineering, Zagreb, Croatia
Marijana Serdar PhD, Higher assistant, Department of materials, Faculty of Civil Engineering, Zagreb, Croatia
Marija Jelcic Rukavina, PhD, Assistant, Department of materials, Faculty of Civil Engineering, Zagreb, Croatia
Ana Baričević, Assistant, Department of materials, Faculty of Civil Engineering, Zagreb, Croatia
Martina Pezer, Assistant, Department of materials, Faculty of Civil Engineering, Zagreb, Croatia

proizvede preko 750 milijuna m³ betona, što bi značilo da stanovnik Europe godišnje upotrijebi četiri tone betona [2]. Takva masovna proizvodnja i potrošnja svrstava betonsku industriju u jednog od najznačajnijih potrošača prirodnih resursa i proizvođača otpada. Istovremeno, betonska industrija ima velike potencijale za promjenu poslovanja prema održivijoj proizvodnji i smanjenju ekološkog otiska. Jedna od mogućih strategija jeste korištenje otpadnih materijala i nusproizvoda iz drugih industrija, kao vrijednih sirovina u betonskoj industriji, približavajući na taj način betonsku industriju što više kružnom modelu industrija. Ovakvo zatvaranje kruga moguće je samo ako se u obzir uzmu svojstva pojedinog otpadnog materijala, te se ta svojstva iskoriste kako bi se poboljšalo neko svojstvo betona ili ostvarila neka dodatna tehnička vrijednost betonskog proizvoda.

Temelji održivosti u industriji betona sastoje se od smanjenja emisije CO₂, očuvanja prirodnih resursa i gradnje trajnijih građevina. Svi navedeni temelji mogu biti obuhvaćeni pomicanjem betonske industrije prema kružnom modelu, putem opisane tzv. industrijske simbioze, u kojoj je otpad iz jedne industrije vrijedna sirovina za drugu industriju. Postoje mnoge industrije širom svijeta s kojima betonska industrija može stupiti u industrijsku simbiozu, jer tijekom svog proizvodnog procesa proizvode otpadne materijale koji bi se mogli koristiti u betonskoj industriji. Neki od takvih otpadnih materijala jesu pepeli i muljevi iz termoelektrana, željezne industrije, aluminijske industrije, sustava pročišćivača otpadnih voda, jednako kao i samo otpadno staklo ili otpadne automobilske gume. Navedeni materijali imaju ili zanimljiv kemijski sastav, poželjan u betonu, ili pojedina svojstva, koja bi betonskim proizvodima moli osigurati dodatne funkcionalne vrijednosti.

U ovom radu prikazane su neke od mogućnosti upotrebe otpadnih materijala iz drugih industrija za pripremu betonskih proizvoda specifičnih svojstava, čime takvi betonski proizvodi postaju zanimljiva alternativa klasičnom betonu. Prikazani su rezultati izvornih znanstvenih istraživanja provedenih na Zavodu za materijale, Građevinskog fakulteta u Zagrebu, ali i ideje za primjenu takvih ekoloških betona u građevinskoj praksi.

2 SIMBIOZA S DRUGIM INDUSTRIJAMA

2.1 Metalna industrija

U današnje vrijeme, svjetska potrošnja cementa iznosi preko dve i po milijarde tona godišnje [1], a s ubrzanim razvojem nerazvijenih zemalja, očekuje se da će ta brojka u budućnosti još rasti. U Hrvatskoj emisija stakleničkih plinova još je u porastu. 2006. godine specifična emisija CO₂ procijenjena je na 850 kg CO₂/t klinkera, odnosno 700 kg CO₂/t cementa. Dakle, u Hrvatskoj cementna industrija proizvodi oko 8–9 % ukupne emisije CO₂ [3]. Zamjena klinkera drugim cementnim materijalima predstavlja obećavajuću strategiju, s obzirom na to što je ekonomski povoljnija za sve sudionike u cementnoj industriji, a još uvijek nije iskorištena do svoga punog potencijala. Najupotrebljiviji zamjenski materijali za cement mogu se pronaći u metalnoj industriji, budući da oni uglavnom

with generation of waste and emission. With yearly around 750 million m³ of concrete produced in Europe [2], concrete industry today is one of the largest consumers of natural resources and one of the largest waste producers. However, concrete industry has a high potential for a positive shift towards more sustainable production and lower ecological footprint. One of the strategies is to use waste materials and by-products from other industries as valuable raw materials in concrete industry, changing concrete industry from linear model towards circular economy model. This loop can be closed only by taking into account properties of a certain waste material and using them for preparation of special purpose concrete products, in which these properties are favourable. Other strategy is designing concrete tailored for certain environment and service life, making it optimised for that specific purpose.

Postulates of sustainability in construction industry are lowering CO₂ emission, conservation of natural resources and constructing and maintaining more durable concrete structures. All these postulates can be covered by moving towards circular economy in concrete industry, through industrial symbiosis with other industries available in different countries or transforming end-of-life products into valuable raw materials for concrete industry. There are numerous industries around the world that during their production processes create waste that could be used in concrete industry as valuable input material. Some of these wastes include ashes and slurries from thermal plants, steel factory, aluminium factory plants, sewer sludge waste, recycled glass, waste tyres etc. These waste materials have either chemical composition interesting for the application as binding material, or certain property which could add value to concrete.

This paper presents some of the possibilities of utilisation of waste materials from different industries for preparing concrete with specific properties, by which they become technologically attractive alternative to classical concrete. Both scientific research results obtained at Department of Materials, Faculty of Civil Engineering in Zagreb are presented, but also prototype of products produced based on the scientific research.

2 SYMBIOSIS WITH OTHER INDUSTRIES

2.1 Metal factories

Nowadays, the world consumption of cement is more than 2.5 billion tonnes annually [1] and it is expected that this number will rise with the industrialization of developing countries. In Croatia, there is still a growth trend of CO₂ emission. In year 2006, direct CO₂ emission from cement industry was around 2.5 million tonnes, which is compared to year 1990 growth of 51 %. In year 2006, specific CO₂ emission was estimated to be 850 kg CO₂/t of clinker or 700 kg CO₂/t of cement. That means that in Croatia cement industry causes around 8–9 % of total CO₂ emission [3]. Clinker substitution is a promising solution as it is a low-cost option that has not yet been used to the greatest possible extent, and, as such, still has great potential. The most common supplementary materials can be found as waste

imaju kemijski sastav koji je zanimljiv u kemiji cementa. Neki od takvih materijala jesu zgura, silicijska prašina i crven mulj. Oni mogu biti pomiješani s drugim mineralnim dodacima komplementarnog kemijskog sastava, poput letećeg pepela, kamene prašine ili aktivirani alkalnim aktivatorima, te na taj način postati alternativna veziva u betonu. U svakom slučaju, kako bi se upotreba takvih otpadnih materijala povećala, nužno je proizvesti veziva koja imaju svojstva što sličnija klasičnim cementima [4, 5].

materials from metal factories, such as granulated blast furnace slag, silica fume or red mud. They can be mixed with other waste materials, such as fly ash, stone quarries etc. However, in order to create market acceptance, the properties of these binding materials have to be comparable with Portland cement [4, 5].

*Slika 1. Zgura i crveni mulj
Figure 1. Slag and red mud*

Eksperimentalna istraživanja provedena na betonima pripremljenim s miješanim cementima, u kojima je zamijenjen veći dio cementa kombinacijom zgre, letećeg pepela i vapnenca, pokazala su da takva zamjena cementa otpadnim materijalima utječe pozitivno na trajnosna svojstva betona (propusnost, rana pojava pukotina) [6-8]. Iako svaki od pojedinih mineralnih dodataka ima specifičan utjecaj na beton, koji nije nužno uvijek pozitivan, kada se dodaju u kombinaciji, njihov sinergijski učinak na svojstva betona jeste pozitivan, što je vidljivo i na slici 2 [8]. U istraživanju od 45 do 55% cementa zamijenjeno je navedenom kombinacijom otpadnih materijala. Referentna mješavina je bila identičnog sastava kao beton korišten prilikom gradnje Masleničkog mosta, koji se nalazi u agresivnom morskom okolišu (oznaka PC). Cement korišten u svim betonima bio je CEM II/A – S 42.5R. Od kemijskih dodataka u mješavinama je korišten superplastifikator, aerant te usporivač vezanja, pa je vodovezivni omjer u svim mješavinama bio 0,4. U drugoj mješavini (oznaka 55% PC) cement je djelomično zamijenjen s 15% zgre, 25% letećeg pepela i 5% vapnenca. U trećoj mješavini (oznaka mješavine 45% PC) cement je zamijenjen s 18% zgre, 32% letećeg pepela i 5% vapnenca. Ispitivanje tlačne čvrstoće provedeno je na tri uzorka kocke dimenzije 150 mm nakon tri dana i dvadeset osam dana njegovanja u vlažnoj komori (95% vlažnost i 20±4°C temperatura), sve prema normi EN 12390-3. Koeficijent difuzije ispitan je prema normi NT BUILD 492, na valjcima promjera 10 cm, visine 5 cm, nakon dvadeset osam dana starosti. Prije ispitivanja, vlažni uzorci su kondicionirani u saturiranoj otopini kalcijevog-hidroksida, sve prema navedenoj normi.

Experimental research performed on concrete mixtures with quaternary-blended cements, substituting large part of Portland cement with combination of slag, fly ash and limestone shows that the substitution of cement with by-products of other industries can have a positive influence on concrete durability properties (penetrability of fluids and ions, early age cracking) [6-8]. Even though a single type of mineral admixture can have different influence on a specific concrete property, synergic influence of mix of mineral can be achieved. In the present research 45 to 55 % of cement was substituted by combination of slag, fly ash and limestone. The referent mixture (labelled PC) was concrete identical to that used during construction of Maslenica Bridge, which is exposed to aggressive marine environment. Cement used in all mixtures was CEM II/A – S 42.5R. In all mixtures superplasticizer, air entraining admixture and retarder were used and water-to-binder ration was kept 0,4. In the second mixture (labelled 55% PC) cement is substituted with 15% of slag, 25% of fly ash and 5% of limestone filler. In the third mixture (labelled 45% PC) cement is substituted with 18% of slag, 32% of fly ash and 5 % of limestone filler. Compressive strength was tested on three cubes dimension 150 mm after 3 and 28 days of curing in chamber (95% relative humidity and temperature 20±4°C), all according to the standard EN 12390-3. Chloride migration coefficient was tested according to the standard NT BUILD 492, on cylindrical samples (dimensions diameter 10 cm, height 5 cm), after 28 days of curing. Before testing, samples were conditioned in saturated calcium hydroxide solution, all according to the stated standard.

Slika 2. Tlačna čvrstoća i koeficijent difuzije kloridnih iona kod betona pripremljenog s cementom i betona pripremljenih s 45 i 55% zamijene cementa kombinacijom mineralnih dodataka (zgura, leteći pepeo i vapnenac)

Figure 2. Compressive strength and chloride diffusion coefficient of concrete prepared with Portland cement and concrete where 45% and 55% of cement is substituted by mineral additions

Rezultati ispitivanja tlačne čvrstoće, slika 2a, pokazuju da se zamjenom velike količine cementa i pravilnom kombinacijom materijala mogu dobiti betoni jednakih razreda čvrstoća, kao i beton pripremljen samo s cementom. S obzirom na sporiji prirast čvrstoće u slučaju betona s letećim pepelom i zguram, očekivano je da bi se pri starosti od 90 dana dobili još povoljniji rezultati za mješavine sa zamjenom cementa. Rezultati ispitivanja prodora klorida (slika 2b) potvrđuju da se kombinacijom navedenih otpadnih materijala može pripremiti beton znatno povećanog otpora prodora agresivnih tvari, što čini ovakve betona zanimljive za upotrebu u morskom okolišu.

Osim često istraživane zgure, koja je već pronašla svoju upotrebu u cementnoj industriji, postoje i drugi nusproizvodi metalne industrije koji se mogu koristiti u pripremi cementa, a crveni mulj je sigurno jedan od njih. Crveni mulj nastaje prilikom proizvodnje aluminija i to u količini od oko 0,5 – 2,5 tone za proizvodnju 1 tone Al_2O_3 . Oko 70% čestica crvenog mulja su veličine od 20 μm , mulj je uobičajeno bogat aluminijevim i željezovim oksidima, te sama otopina ima izrazito veliku pH vrijednost. Istraživanja do sada provedena i dostupna iz literature pokazuju da dodavanje više od 20% crvenog mulja cementu značajno smanjuje toplinu hidratacije i u konačnici tlačnu čvrstoću [9, 10]. Određena istraživanja koriste spaljivanje mulja pri visokim temperaturama ili alkalnu aktivaciju kako bi postigla bolja svojstva betona s dodatkom crvenog mulja. U istraživanju, crveni mulj, zajedno s letećim pepelom i vapnencem, aktiviran je s malom količinom cementa CEM II, kako bi se pripremili betoni visokih uporabnih svojstava [11]. Korišten cement CEM II B-M (S-V) 42.5 N već u samom sastavu sadrži 65 do 79% klinkera i 21 do 35% zgure i silicijskog letećeg pepela. Kada se uzme u obzir zamjena cementa s dodatnim letećim pepelom, crvenim muljem i vapnencem, pripremljena i ispitana mješavina prikazana u radu sadrži dakle samo 25% klinkera. Nakon dvadeset osam dana, tlačna čvrstoća ove mješavine bila je 38 N/mm^2 , dok je nakon devedeset dana iznosila 57 N/mm^2 . Na slici 3 prikazani su rezultati razvoja koeficijenta difuzije klorida nakon dvadeset osam dana starosti betona, te mjerenje deformacije skupljanja uslijed sušenja od tri do pedeset šest dana starosti

Results of compressive strength testing, Figure 2a, show that with the substitution of higher amount of cement with certain combination of waste materials, it is possible to obtain concrete with the same strength class as concrete prepared with cement. Furthermore, it can be anticipated that after longer time of curing (90 days) compressive strength of blended cement concrete would be even more satisfying, due to the expected slower rate of hydration of slag and fly ash. Results of chloride migration testing, Figure 2b, are confirming that with the combination of blended materials, concrete with higher resistivity to penetration of fluids is obtained. These concrete mixtures could therefore be used in the aggressive marine environment.

Beside blast furnace slag, which found its application in cement industry, there are other by-products of metal factories which could be potential candidates as binding material, and red mud is surely one of them. Red mud is obtained as a by-product of aluminium industry, with generation of around 0.5 – 2.5 tonnes of red mud during production of 1 tonne of Al_2O_3 . Around 70% of particles are around 20 μm , it is generally rich in aluminium and iron oxides and has a high pH value. Performed research shows that the addition of red mud in amount higher than 20% causes decrease in hydration temperature and resulting decrease in compressive strength [9, 10]. Some researcher used calcination on high temperatures or alkali activation of red mud to achieve better performances of concrete. In this research, red mud was used together with fly ash and limestone in Portland cement with slag to prepare concrete with increased durability properties and decreased shrinkage [11]. Cement type CEM II B-M (S-V) 42.5 N was used, which already has 65 to 79% clinker and 21 to 35% of slag and siliceous fly ash. When cement composition is taken into account, together with the addition of red mud, fly ash and limestone, prepared and tested mixture actually has only 25% of clinker. After 28 days compressive strength of this mixture is 38 N/mm^2 , while it reaches 57 N/mm^2 after 90 days of curing. Figure 3 shows evolution of chloride diffusion coefficient after 28 days of concrete curing, as well as monitoring of deformation due to the drying shrinkage of concrete. Coefficient of chloride

betona. Koeficijent difuzije ispitivan je prema normi NT BUILD 492, na tri valjka promjera 100 cm, visine 5 cm. Skupljanje uslijed sušenja mjereno je na tri uzorka prizme dimenzija 100×100×400 mm. Uzorci su dan nakon miješanja izvađeni iz kalupa, te njegovani 48 sati u vodi. Sedamdeset dva sata nakon miješanja, na uzorke su postavljeni reperi na udaljenosti od 200 mm. Tijekom cijelog vremena mjerenja, uzorci su držani u komorama s kontroliranom vlažnošću od 70±5%.

Slika 3. Koeficijent difuzije kloridnih iona betona pripremljenog s cementom CEM II i betona u kojem je značajan dio cementa zamijenjen crvenim muljem, letećim pepelom i vapnencem

Figure 3. Chloride diffusion coefficient of concrete prepared with CEM II and concrete with CEM II red mud, fly ash and limestone [11]

Iz rezultata ispitivanja koeficijenta difuzije (slika 3a), vidljivo je da mješavina sa značajnom zamjenom cementa otpadnim materijalima ima poboljšana svojstva propusnosti, te nakon pedeset šest dana doseže vrlo niske vrijednosti prodora klorida. Moguće je zaključiti da dolazi do sinergijskog djelovanja različitih otpadnih materijala i njihovog različitog kemijskog sastava i veličine čestica. Iz rezultata mjerenja deformacije uslijed skupljanja, vidljivo je da uslijed smanjene količine cementa i potencijalno pozitivnog učinka otpadnih materijala, dolazi do smanjene deformacije skupljanja uslijed sušenja. S obzirom na poboljšanje svojstava propusnosti betona, te smanjenog rizika pojave pukotina uslijed sušenja betona, navedene mješavine mogle bi se koristiti za pripremu betonskih predgotovljenih elemenata za prometnice, poput rubnjaka, vijenaca, barijera, slivnika i slično. Upravo ova vrsta betonskih elemenata nekontrolirano propada na prometnicama uslijed dugotrajnog izlaganja agresivnom okolišu, bilo uslijed smrzavanja i odmrzavanja ili vlaženja i sušenja uz prisustvo soli (morske ili za odmrzavanje). Korištenjem predložene mješavine veziva mogle bi se ostvariti ekološke uštede; s obzirom na to što se koristi manje Portland cementa, smanjena je i emisija CO₂, a korištenjem otpadnih materijala smanjeno korištenje neobnovljivih prirodnih materijala. Istovremeno, takva primjena imala bi tehnološke prednosti, s obzirom na povoljnija svojstva betona, te moguće ekonomske prednosti, s obzirom na cijenu otpadnih materijala i veći uporabni vijek betonskih proizvoda.

migration was measured according to standard NT BUILD 492 on three samples. Drying shrinkage was measured on three prisms dimension 100×100×400 mm. Specimens were one day after mixing demoulded and water cured for 48 hours. Afterwards, measuring pins were glued on both sides of sample and they were placed in chamber with controlled humidity (70±5%).

From the results of chloride migration testing, Figure 3a, it can be observed that, with a significant substitution of cement with chosen waste materials, concrete has enhanced penetrability properties, with extremely low coefficient achieved after 56 days of curing. It can be concluded that there is a synergic effect of different waste materials, with their complementary chemistry and particle size distribution. From the results of deformation during drying shrinkage, Figure 3b, it can be observed that, due to the lower amount of cement, but also potential beneficial effect of waste materials, deformation due to drying shrinkage is decreasing. Since most of the blended mixtures have increased durability properties, they could find application in the production of precast concrete elements used for infrastructures, such as concrete cornice, traffic barriers, curbs, outlet channels, etc. Due to the aggressive exposure of such elements, with wetting, drying and splashing with additives for de-freezing, they are usually one of the first parts of bridges that experience premature deterioration due to corrosion and freezing and thawing. Using blended mixtures for such applications would lead to ecological benefits, since by using less Portland cement amount of produced CO₂ emission is lowered and by using waste materials natural resources are preserved. At the same time, such application would provide technological benefits, since decreased penetrability of concrete leads to increased durability of elements, all consequently leading to significant economic benefits.

2.2 Termoelektrane

Leteći pepeo nastaje kao nusproizvod izgaranja ugljena u termoelektranama (slika 4). Čestice letećeg pepela su sferičnog oblika, male veličine, a velike specifične površine. S obzirom na uobičajeno sporiju hidrataciju letećeg pepela [12-15], korištenje pepela u betonu smanjuje toplinu hidratacije, te je zbog toga leteći pepeo našao primjenu u masivnim betonskim konstrukcijama, poput temelja, mostova, molova i brana.

Slika 4. Termoelektrana Plomin i leteći pepeo koji nastaje kao otpadni materijal
Figure 4. Thermal power plant and fly ash left as waste material

Osim poboljšanih trajnosnih svojstava, korištenjem mineralnih dodataka u betonu može se utjecati na poboljšanje preostalih svojstava betona nakon izloženosti visokim temperaturama, pa se spomenuta uporaba betona s letećim pepelom može proširiti i na konstrukcije koje će u svom vijeku trajanja biti izložene visokim temperaturama. Provedeno je eksperimentalno istraživanje utjecaja visokih požarnih temperatura (do 600°C u materijalu) na mehanička svojstva (tlačna čvrstoća i modul elastičnosti) samozbijajućih betona s malim vodopraškastim omjerom ($v/p = 0,27$), u kojem je dio Portland cement (CEM I 42,5R) zamijenjen s različitim mineralnim dodacima [12, 13], među kojima je i leteći pepeo iz termoelektrane Plominu količini 20–40% na masu cementa. Osim navedenih sastojaka, mješavine samozbijajućeg betona sadržavale su dolomitni filer, dolomitni agregat, te superplastifikator i stabilizator mješavine u količini potrebnoj da se postigne rasprostiranje slijeganjem od 700 ± 50 mm.

Rezultati istraživanja prikazani na slikama 5 i 6 pokazuju da mješavine s letećim pepelom u temperaturnom području do 400°C imaju bolja preostala svojstva tlačne čvrstoće i modula elastičnosti u odnosu na referentnu mješavinu. Pozitivan učinak letećeg pepela očituje se prvenstveno u naknadnoj pucolanskoj reakciji letećeg pepela i kalcijevog hidroksida uslijed kretanja slobodne vlage u betonu koja je uzrokovana visokom temperaturom. Manja količina kalcijevog hidroksida u mješavinama s letećim pepelom, nadalje, doprinosi i stvaranju manjeg broja pukotina u cementnoj matrici (vidljivo na slici 6), budući da se kalcijev hidroksid raspada na temperaturama višim od 350°C na vapno i vodu stvarajući pukotine u mikrostrukтури betona [14].

2.2 Thermal power plants

Fly ash is a by-product of the combustion of coal in electric generating plants, Figure 4. Particles of fly ash are glassy and spherical in shape, small in size and large in specific area. Due to its generally slower rate of hydration [12-15], fly ash lowers the heat of hydration and is important in mass concrete structures, such as large foundations, bridges, and piers.

Besides enhancing concrete durability properties, utilisation of mineral additions in concrete can positively influence residual properties of concrete after exposure to high temperatures. Therefore, the application of concrete with blended cement can be interesting for structures with a risk of being exposed to fire during service life. Present experimental research was performed with a purpose of investigating the effect of high temperatures occurring during fire (up to 600°C in material) on mechanical properties (compressive strength and modulus of elasticity) of self-compacting concretes with low water-to-powder ratio ($v/p = 0,27$). Self-compacting concrete was prepared with high substitution of Portland cement (CEM I 42,5R) with mineral additions [12, 13], among them fly ash from thermal power plant Plomin, in amount of 20-40% on cement weight. Mixtures were prepared with dolomite filler, dolomite aggregate, superplasticizer and viscosity modifying agent in the amount to achieve slump flow of 700 ± 50 mm.

Results presented on Figure 5 and 6 show that mixtures with fly ash have better residual properties for temperature ranges up to 400°C, compared to mixture with pure Portland cement. The positive effect of fly ash is mostly obtained through postponed hydration reaction between fly ash and portlandite and flow of free water due to the exposure to high temperatures. Lower amount of portlandite in mixtures with fly ash is furthermore contributing to lower amount of cracks formed in cement matrix (Figure 6), since portlandite is decomposing at temperatures higher than 350°C to lime and water, consequently forming cracks in the matrix [14].

a) b)

Slika 5. Preostala svojstva a) tlačne čvrstoće i b) modula elastičnosti mješavina samozbijajućeg betona nakon izlaganja visokoj temperaturi
Figure 5. Residual properties a) compressive strength and b) modulus of elasticity of SCC mixtures after exposure to high temperature

a) b)

Slika 6. SEM snimci a) referentne mješavine i b) mješavine sa 40% zamjene cementa letećim pepelom nakon djelovanja temperature od 400°C
Figure 6. SEM images of a) referent mixture and b) mixture with 40% substitution of cement with fly ash after exposure to 400°C

2.3 Sustavi za pročišćavanje otpadnih voda

Prilikom pročišćavanja otpadnih voda, u sustavima za pročišćavanje nastaje otpadni mulj i to u količinama od oko 0,5 kg za svaki m³ otpadne vode. Pod pravilnim gospodarenjem otpadnim vodama smatra se prikupljanje, dopremanje do sustava, te tretiranje otpadne vode i ispuštanje čiste, kao i pravilno zbrinjavanje otpada nastalog postupkom pročišćavanja. Spaljivanje mulja pročišćivača otpadnih voda uvelike olakšava zbrinjavanje novonastalog proizvoda, pepela dobivenog iz mulja otpadnih voda. Znanstvena istraživanja iz literature prikazuju da bi se spaljeni mulj, s obzirom na kemijski sastav i svojstva, mogao koristiti u građevinskoj industriji, u proizvodnji betona, cementa, opeke, asfalta i ostaloga [16,17].

2.3 Water treatment plants

In the wastewater treatment, additional waste called sewage sludge is generated, with around 0.5 kg of sludge on a dry mass basis per 1 m³ of wastewater. Adequate wastewater management (sanitary and industrial in the first place) implies collecting, transport and treatment of wastewater, but also adequate management of waste substances generated by treatment. Incineration of sewer sludge considerably facilitates further management of the new product (incinerated sewage sludge ash - ISSA), since a significant reduction in mass occurs. Scientific research has shown that the generated sewage sludge, with regard to its properties and chemical composition may be reused in construction industry in production of cement, concrete, bricks, ceramics, asphalt compounds in road construction etc. [16,17].

Slika 7. Sustav za pročišćavanje otpadnih voda u Zagrebu i pepeo nastao spaljivanjem mulja otpadnih voda [18]
Figure 7. Water treatment plant and incinerated sewage sludge obtained as by-product [18]

Trenutno se na Građevinskom fakultetu u Zagrebu provode opsežna ispitivanja mogućnosti korištenja pepela dobivenog spaljivanjem mulja otpadnih voda kao zamjene dijela cementa u betonu. Dosadašnja saznanja ukazuju na određenu pucolansku aktivnost pepela mulja otpadnih voda. Također, značajne količine SiO_2 i Al_2O_3 koje se nalaze u zagrebačkom pepelu ukazuju na to da postoji realna mogućnost ovakve primjene pepela. No, nužno je pronaći najoptimalniju metodu aktivacije pepela, kroz miješanje s komplementarnim mineralnim dodacima, te pronaći specifična područja primjene u kojima bi betoni pripremljeni s pepelom mulja otpadnih voda, s obzirom na svojstva, bili zanimljiva alternativa klasičnom betonu.

Currently at the Faculty of Civil Engineering research is being performed to evaluate the potential of application of incinerated sewage sludge ash as a substitution of cement. Numerous analyses showed a certain degree of pozzolanic activity of ISSA. Considerable contents of SiO_2 and Al_2O_3 in ISSA indicate the possibility of using this material as binder. It is necessary to find the optimum method for activation of ISSA generated by incineration process of sewage sludge. Reactivity of locally available ISSA from sewage sludge should be viewed from the aspect of micro-texture, chemical and mineralogical composition and pozzolanic activity, in various conditions of incineration process, adding of various additives and during concrete batching.

3 KRAJ ŽIVOTNOG VIJEKA - POČETAK NOVOGA

3 END-OF-LIFE - NEW BEGINNING

3.1 Otpadne gume

3.1 Waste tyres

Samo na području zemalja članica Europske unije, godišnje nastane gotovo 3,4 milijuna tona otpadnih guma [19]. Noviji podaci pokazuju na to da se u zemljama EU 15 nekontrolirano odlaže samo 5% ukupne količine otpadnih guma. Istovremeno, procjenjuje se da se na području novih članica EU i zemalja pristupnica godišnje nekontrolirano odlaže 29% nastalih otpadnih guma. Sukladno Direktivi 1999/31/EC, počevši od 2006. godine, svako je odlaganje otpadnih guma u okoliš potpuno zabranjeno, pa je tom odlukom raspoloživa količina otpadnih guma znatno porasla. Hrvatska je nacionalne propise harmonizirala s EU Direktivama u pogledu postupanja s otpadnim gumama. Drugim riječima, 70% otpadnih guma trebalo bi reciklirati, dok se 30% može koristiti u energetske svrhe.

Every year about 3.4 million tonnes of waste tyres are generated in Europe [19]. In the EU15, only 5 % of waste tyres are uncontrollably disposed in landfills. In the 12 new EU member states and Western Balkan, averagely 29 % of waste tyres are disposed in landfills, annually. With the introduction of EU Directive 1999/31/EC of 26 April 1999 on the landfill of waste in those countries, which bans landfilling of whole (July 2003) and shredded (July 2006) tyres, it is clear that there is need to increase recycling capacities and develop markets for utilising recycled tyres. The Republic of Croatia harmonized its regulations with the EU Directives relating to the assessment and management of waste tyres. In other words, 70 % of all waste tyres should be processed through material recycling and other 30% can be reused as energy source.

Slika 8. Guma, čelična i tekstilna vlakna dobivena reciklažom otpadnih guma
Figure 8. Rubber, steel fibres and textile fibres from recycled end-of-life tyres

Opsežno istraživanje pokazalo je da se svaki od proizvoda dobivenih reciklažom otpadnih guma (slika 8) može koristiti u betonu, te istovremeno poboljšati određena svojstva betona [20-23]. U suradnji sa industrijskim partnerima, razvijena su dva inovativna proizvoda, a u sklopu novog EU projekta planira se razviti još inovativnih proizvoda, iskorištavaju pojedina svojstva reciklata automobilske gume kako bi se pripremili specifični betonski proizvodi.

Lagani apsorpcijski sloj betonske barijere za zaštitu od buke RUCONBAR razvijen je uz korištenje velikog volumenskog udjela granulata reciklirane gume u mješavini betona, čime se osigurava velika razina apsorpcije zvuka, te zadovoljavajuća mehanička i trajnosna svojstva proizvoda. RUCONBAR direktno djeluje na dva ekološka problema – zagađenje bukom [24] i gospodarenje otpadom. Eksperimentalna istraživanja započela su 2009. godine, a danas RUCONBAR ima međunarodni certifikat kojim se potvrđuje da proizvod zadovoljava sve tehničke zahtjeve za barijere za zaštitu od buke na prometnicama [25].

The extensive research performed on University of Zagreb Faculty of Civil Engineering implied positive effects when those are incorporated in concrete, either as replacement for raw materials or as a certain chemical admixtures [20-23]. In cooperation with industrial partners, researchers from the University of Zagreb, Faculty of Civil Engineering have developed two different construction products, which are utilising particular property of recycled tyres, to create solutions with added values on the market.

Lightweight rubberized concrete noise barrier RUCONBAR was developed by incorporating high volume of rubber particles in concrete mix, ensuring high level of noise absorption and insulation, but at the same time providing satisfying mechanical and durability behaviour. RUCONBAR reaches two major environmental problems, noise pollution [24] and waste tyres management. Experimental research started in 2009 in the laboratory and today after extensive optimisation and testing, research based product RUCONBAR, has a certificate showing it satisfies all necessary properties for application on infrastructures as noise protection barrier [25].

Slika 9. Betonske barijere za zaštitu od buke s recikliranom gumom – RUCONBAR
Figure 9. Rubberized concrete noise barrier RUCONBAR

Mikroarmirani hibridni beton sa čeličnim vlaknima i gumenim granulatom za proizvodnju betonskih pragova, ECOTRACK, jeste inovativni ekološki proizvod suvremenog željezničkog kolosijeka. Proizvod se sastoji od dvodijelnih betonskih pragova ugrađenih u betonsku ploču, te zajedno čine čvrstu betonsku kolosiječnu konstrukciju. Iako su slična rješenja prisutni na tržištu, ECOTRACK uključuje primjenu sastojaka reciklaže otpadnih guma kao zamjenu dijela uobičajenih prirodnih sirovina [26].

Korištenjem mikroarmiranog hibridnog betona sa čeličnim vlaknima i gumenim granulatom osigurava se sposobnost opiranja konstrukcije različitim uvjetima opterećenja. Štoviše, sprječava se pojava prvih pukotina i time je omogućena veća trajnost takvog građevinskog elementa. Sukladno očekivanjima, početna ispitivanja ECOTRACK-a potvrdila su mogućnost primjene ekološki prihvatljivih resursa (proizvoda reciklaže) za proizvodnju betona visokih uporabnih svojstava posebne namjene [23]. Na slici 10 prikazani su rezultati ispitivanja postpukotinskog ponašanja mješavine mikroarmiranog betona pripremljene s industrijskim vlaknima, te rezultati ispitivanja mješavina u kojima je 50 i 100% vlakana zamijenjeno recikliranim čeličnim vlaknima iz automobilske gume. Iz rezultata je vidljivo da se, kada se

Rubberized hybrid steel fibre reinforced concrete for production of concrete track systems, ECOTRACK, is an eco-innovative product of a modern high speed railway structure. Solution is made of two-part concrete sleepers built in the concrete slab, together making a ballastless concrete track system. Although, similar solutions are already present on the market ECOTRACK incorporates by-products from mechanical recycling of waste tyres as a replacement for usual natural raw materials [26].

The usage of rubberized hybrid fibre reinforced concrete elements assures an adequate resistance ability of the structure under various strain conditions. Furthermore, the appearance of first cracks on concrete surface is prolonged and thus a higher durability of such construction elements is achieved. In accordance with the starting expectations, the initial testing of the ECOTRACK confirmed the possibility of the application of ecologically acceptable resources (recycling products) for the production of high performance concrete for special application [23]. Figure 10 shows the results of post-cracking behaviour of fibre reinforced concrete mixes prepared with industrial fibres, and of mixes where 50 and 100% of industrial fibres were substituted with fibres from end-of-life tyres. From the results it can be observed that when industrial fibres are substituted with

umjesto industrijskih vlakana koriste reciklirana vlakna iz automobilske gume, smanjuje količina energije koju beton apsorbira nakon sloma. Potrebno je naglasiti da su industrijska vlakna korištena u prikazanom istraživanju značajnije veća od recikliranih vlakana, 35 mm duljine i 0.55 mm promjer naspram 15 mm duljine i 0.18 mm promjer. Također, industrijska vlakna izvedena su sa zakrivljenim krajevima, što povećava njihovu prionjivost u cementnoj matrici. S druge strane, iz prikazanih rezultata također je vidljivo da se kombiniranjem industrijskih i recikliranih vlakana dobivaju poboljšanja svojstava, u odnosu na betone pripremljene samo s recikliranim vlaknima. Dakle, moguće je zaključiti da su u pogledu primjene u građevinskoj industriji zanimljive kombinacije te dvije vrste vlakana, kako bi se osigurale prednosti mikroarmiranih betona, te istovremeno postigle ekološke i ekonomske uštede.

the recycled ones, there is a loss of post-cracking energy absorption. However, it is necessary to highlight that the industrial fibres used are significantly longer than recycled fibres, 35 mm length with 0.55 mm diameter, compared to 15 mm length and 0.18 mm diameter. Furthermore, used industrial fibres had hooked ends, which is additionally increasing their anchorage in the cement matrix. At the same time, from the presented results it can be observed that with the combination of industrial and recycled fibres it is possible to achieve enhanced properties, compared to only recycled fibres. Therefore, it is possible to conclude that the combination of these two fibres would be potentially interesting for the practical application, since technical benefits of fibre reinforced concrete can be achieved, together with both ecologic and economic savings.

Slika 10. Ponašanje hibridnih kompozita s različitim udjelom industrijskih i recikliranih čeličnih vlakana
Figure 10. Behaviour of hybrid composites with different ratio between industrial and recycled fibres in the total amount of fibres [23]

Upravo je primjena svih produkata reciklaže otpadnih automobilske gume za izradu betonskih proizvoda konstruktivna, ali i druge namjene, znanstveni i tehnološki izazov novog EU FP7 projekta Anagenisis [27]. U sklopu projekta, planira se prevladavanje tih izazova, inovacijama u novim održivijim tehnologijama i inovativnim ekološkim proizvodima. Cilj projekta je primjena svakog od produkata reciklaže automobilske gume (čelična vlakna, gumeni granulati, tekstilna vlakna) u pripremi betonskih proizvoda, u kojima se koriste određena svojstva produkata reciklaže za poboljšavanje svojstava gotovog betonskog proizvoda. Tako se putem projekta razvijaju mikroarmirani betoni s recikliranim čeličnim vlaknima za poboljšanje postupotinskog ponašanja betonskih elemenata, te betoni s recikliranim tekstilnim vlaknima za sprječavanje pojave mikropukotina uslijed skupljanja betona. Gumeni granulati koriste se za razvoj betonskih elemenata poboljšane deformabilnosti. Naposljetku, osnovni cilj projekta je uvođenje inovativnih kombinacija materijala, uz pomoć industrijskih partnera u proizvodnju industrijskih podova i estriha, predgotovljenih elemenata i mlaznih betona za stabilizaciju pokosa.

It is exactly this implementation of waste tyre recycling products for preparation of innovative concrete products that is the main scientific and technological challenge of recently approved EU FP7 project Anagenisis [27]. Within the project these challenges are planned to be overcome through innovation in new sustainable technologies and innovative ecological products. The aim of the project is to utilise each one of the waste tyres recycling products (steel fibres, textile fibres and rubber granulates) in concrete products, where properties of recycling products are used to enhance certain properties of concrete products. For example, within the project fiber reinforced concrete with recycled steel fibers is being developed, for enhanced post-cracking behaviour of concrete elements. Concrete with textile fibers is prepared for higher resistance to microcracking due to shrinkage of concrete. Rubber granulates are used to prepare concrete elements with better deformability properties. At the end, the main goals of the project is to apply these innovative combinations of materials, with the help of industrial partners in the project, in real-scale production of industrial floors and screeds, precast concrete elements and sprayed concrete for slope stabilisation.

4 ZAKLJUČAK

Betonska industrija ima veliki potencijal za pomicanje prema održivoj proizvodnji i smanjenom ekološkom otisku. U članku su prikazane neke od mogućnosti, putem industrijske simbioze s metalnom industrijom, sustavima za pročišćavanje otpadnih voda ili termoelektrane ili korištenjem recikliranih proizvoda nakon kraja njihovog uporabnog vijeka. Korištenjem otpadnih materijala kao sirovina sa smanjenom energijom potrebnom za proizvodnju i sirovina s poželjnim svojstvima, moguće je pripremiti betonske proizvode sa ekološkim, tehnološkim i ekonomskim prednostima.

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4 CONCLUSIONS

Concrete industry has a high potential for a positive shift towards more sustainable production and lower ecological footprint. Paper shows some of these possibilities, through industrial symbiosis with metal factories, waste water treatment plants or thermal power plants, and through reuse of waste products with favourable properties, such as end of life tyres. Using raw materials with lower embodied energy (waste or reused materials) and favourable properties can lead to creation of concrete products with ecological, technological and economic benefits.

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REZIME

MOGUĆNOSTI PRIBLIŽAVANJA BETONSKE INDUSTRIJE CIRKULARNOM MODELU KROZ INDUSTRIJSKU SIMBIOZU

Dubravka BJEGOVIĆ
 Marijana SERDAR
 Marija JELČIĆ RUKAVINA
 Ana BARIČEVIĆ
 Martina PEZER

Glavni problemi tradicionalne betonske industrije jesu korištenje velike količine neobnovljivih resursa i emisija stakleničkih plinova tijekom proizvodnje, korištenja i rušenja betonskih konstrukcija. Istovremeno, betonska industrija ima velike potencijale za pozitivan pomak prema održivoj proizvodnji i smanjenju negativnog ekološkog utjecaja. Jedna od mogućih strategija jeste korištenje otpadnih materijala i nusproizvoda iz drugih industrija kao vrijednih sirovina u betonskoj industriji. Ovako zatvaranje kruga moguće je samo ako se u obzir uzmu svojstva pojedinog otpadnog materijala, te se ta svojstva iskoriste prilikom projektiranja betona specijalne namjene, u kojima su ta svojstva poboljšana. Druga strategija je projektiranje betona za određeni razred izloženosti okoliša i njegov životni vijek, tj. optimizacija betona za specifičnu namjeru.

Rad prikazuje neke od dostupnih otpadnih i recikliranih materijala u Hrvatskoj, te istraživanja mogućnosti njihove upotrebe u građevinarstvu. Mogućnosti primjene otpadnih i recikliranih materijala su prvo razmatrane u laboratorijskim uvjetima, te su u radu prikazani znanstveni rezultati tih istraživanja. Na temelju znanstvenih istraživanja, ponuđene su neke od mogućnosti primjene takvih materijala u specifične svrhe, gdje oni postaju tehnološki atraktivna alternativa klasičnim betonima. Predstavljeni su rezultati izvornih znanstvenih istraživanja te prototipi proizvoda proizvedeni na temelju tih istraživanja.

Ključne riječi: emisija CO₂, recikliranje, alternativni cementni materijali, otpadne gume

SUMMARY

POSSIBILITIES IN CONCRETE INDUSTRY TOWARDS CIRCULAR ECONOMY THROUGH INDUSTRIAL SYMBIOSIS

Dubravka BJEGOVIĆ
 Marijana SERDAR
 Marija JELČIĆ RUKAVINA
 Ana BARIČEVIĆ
 Martina PEZER

Major challenges of traditional linear concrete industry are utilisation of large amount of non-renewable resources and significant air emissions during production, utilisation and demolition of concrete structures. At the same time, concrete industry has a high potential for a positive shift towards more sustainable production and lower ecological footprint. One of the strategies is to use waste materials and by-products from other industries as valuable raw materials in concrete industry. This loop can be closed only by taking into account properties of a certain waste material and using them for preparation of special purpose concrete products, in which these properties are favourable. Other strategy is designing concrete tailored for certain environment and service life, making it optimised for that specific purpose.

The paper presents some of the available waste and recycled materials in Croatia and research focused on their potential application in civil engineering. The possibilities of utilisation are first explored in laboratory conditions, with the results presented in this paper as an outcome. Based on the obtained results some of the potential areas of application are proposed, in which concrete prepared with these waste materials becomes alternative to classical concrete. Both original scientific research results are presented, but also prototype of products produced based on the scientific research.

Keywords: CO₂ emission, recycling, supplementary cementitious materials, waste tyres