33. SLOVENSKI KOLOKVIJ O BETONIH

33rd SLOVENIAN COLLOQUIUM ON CONCRETE

SAMOZGOŠČEVALNI BETON

SELF-COMPACTING CONCRETE (SCC)

TRZIN, 28. MAJ 2026

irma inštitut za raziskavo materialov in aplikacije d.o.o.

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ZBORNIK GRADIV IN REFERATOV

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Spoštovani!

Samozgoščevalni beton (SCC) je že kar nekaj časa v uporabi v betonerski praksi. Zaradi svoje značilnosti se zelo pogosto uporablja, predvsem pri izdelavi posameznih konstrukcijskih elementov z zelo gosto armaturo in ko je potrebno z betonom zapolniti nedostopna mesta za zgoščevanje. Pri tem pa morajo biti dostikrat dosežene še dodatne lastnosti v strjenem stanju, kar zahteva od vseh udeležencev pri gradnji dodatna znanja pri projektiranju, pripravi, transportu in vgrajevanju.

Med dolgoletno uporabo SCC so se pridobila nova spoznanja in številni rezultati raziskav, kontrolnih preskusov ter stalnih opazovanj vgrajenega SCC, ki so pripomogla k nadaljnjemu razvoju uporabe tega betona.

Pri izvedbi kolokvija sodelujejo povabljeni predavatelji iz Slovenije in tujine, ki bodo predstavili svoje rezultate raziskav in bogate izkušnje iz prakse, ki jih bodo lahko udeleženci kolokvija uporabljali pri svojem delu.

Na kolokviju so predvidene obravnave naslednjih tem (po predvidenih naslovih referatov): prenos tehnologije samozgoščevalnih betonov v slovensko gradbeno prakso – izkušnje UL FGG; izkušnje in omejitve pri uporabi SCC; visokozmogljivi samozgoščevalni cementni kompoziti z notranjo nego na osnovi SAP: projektiranje in aplikacije; možnost uporabe različnih materialov v SCC betonih; izkušnje pri uporabi samozgoščevalnega betona na Hrvaškem; podvodna sanacija in ojačitev stolpa za zajem globoke vode z uporabo tesnilnih obročev iz SCC in injektiranjem poliuretana; uporaba SCC za izdelavo vidnih betonov; vpliv malih sprememb v sestavi SCC na njegovo obdelovalnost.

Tako kot na vseh dosedanjih kolokvijih, so med udeleženci tudi strokovnjaki iz vseh področji gradbene stroke, ki so se v svoji vsakodnevni praksi vsaj enkrat ukvarjali s problematiko projektiranja, priprave in vgrajevanja samozgoščevalnih betonov. Zato pričakujem, da se bodo tudi na tem kolokviju razvile plodne razprave in morda porodile nove ideje, ki jih bo lahko vsak od prisotnih na kolokviju uporabil pri svojem delu. Na ta način bi bil uresničen tudi glavni namen tega kolokvija in prepričan sem tudi vseh naslednjih.

Tako kot vedno, bi se želel še enkrat zahvaliti za prisotnost in interes vseh udeležencev iz Slovenije in iz naše bližnje ter širše okolice. Prav tako pa se moram zahvaliti vsem našim poslovnim partnerjem, ki ste z objavami oglasov v Zborniku gradiv in referatov finančno podprli naš kolokvij in omogočili njegovo izvedbo.

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33. SLOVENSKI KOLOKVIJ O BETONIH

Prenos tehnologije samozgoščevalnih betonov v slovensko gradbeno prakso: izkušnje UL FGG

Transfer of self-compacting concrete technology to Slovenian construction practice: experience of UL FGG

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Povzetek

Samozgoščevalni beton (SCC) predstavlja pomemben razvojni korak v tehnologiji betona, saj omogoča vgradnjo brez mehanskega vibriranja ter zagotavlja izboljšano homogenost, kakovost površine in trajnost konstrukcij. V članku predstavljamo pregled raziskav in razvoja betonov SCC na Univerzi v Ljubljani, Fakulteti za gradbeništvo in geodezijo (UL FGG), ki potekajo od leta 1999 naprej. Raziskave so se začele v okviru razvojno-raziskovalnih projektov za DARS in so bile usmerjene v razvoj ekonomičnih betonov SCC iz lokalnih materialov, predvsem drobljenih apnenčevih agregatov in apnenčeve moke. V nadaljevanju so bile raziskave razširjene na področje obstojnosti betonov SCC, vpliva vrste agregata in kemijskih dodatkov ter razvoja lahkoagregatnih samozgoščevalnih betonov (LSCC). Predstavljene raziskave potrjujejo uspešen prenos tehnologije SCC iz laboratorijskega okolja v gradbeno prakso ter poudarjajo njen prihodnji potencial pri avtomatizaciji in robotizaciji gradbenih procesov.

Abstract

Self-compacting concrete (SCC) represents an important advancement in concrete technology, as it enables placement without mechanical vibration while ensuring improved homogeneity, surface quality, and durability of concrete structures. This paper presents an overview of SCC research and development carried out at the University of Ljubljana, Faculty of Civil and Geodetic Engineering (UL FGG), since 1999. The research started within applied research projects for DARS and focused on the development of economical SCC mixtures based on locally available materials, primarily crushed limestone aggregates and limestone filler. Subsequently, the research was extended to the durability performance of SCC, the influence of aggregate type and chemical admixtures, and the development of lightweight self-compacting concrete (LSCC). The presented research demonstrates the successful transfer of SCC technology from laboratory development to practical application and highlights its future potential in automated and robotized construction processes.

Ključne besede: samozgoščevalni beton (SCC), lahkoagregatni samozgoščevalni beton (LSCC), reologija, obstojnost, apnenčeva moka, robotizacija gradbeništva
Keywords: self-compacting concrete (SCC), lightweight self-compacting concrete (LSCC), rheology, durability, limestone powder, construction robotization

1. UVOD

Samozgoščevalni beton (angl. Self-Compacting Concrete – SCC) predstavlja enega najpomembnejših razvojnih dosežkov na področju tehnologije betona v zadnjih desetletjih, ki je relativno hitro postal del evropskih standardov in sodobne gradbene prakse. Njegova osnovna značilnost je sposobnost, da se razliva, zapolni opaž in popolnoma oblije armaturo samo zaradi delovanja lastne teže. Mehansko vibriranje je v celoti izločeno. Tehnologija betona SCC omogoča izboljšano homogenost betona, zmanjšanje napak pri

vgradnji ter višjo kakovost končnih površin konstrukcijskih elementov. Med ključnimi prednostmi betona SCC izstopajo predvsem izboljšana trajnost zaradi gostejše mikrostrukture, večja zanesljivost kakovostne vgradnje v zahtevnih pogojih (gosta armatura, kompleksne geometrije), zmanjšanje hrupa in izboljšani delovni pogoji na gradbišču ter večja produktivnost pri proizvodnji elementov, ki so izdelani v obratu.

Na Univerzi v Ljubljani, Fakulteti za gradbeništvo in geodezijo (UL FGG), se z raziskavami betonov SCC sistematično ukvarjamo že od konca 90. let prejšnjega stoletja. Prve raziskave na tem področju segajo v leto 1999, ko smo v okviru razvojno-raziskovalne naloge DARS z naslovom Betoni vgradljivi brez kompaktiranja za cestne objekte [1] začeli z razvojem ekonomičnega betona SCC iz lokalnih materialov. Sledile so preiskave, ki so se osredotočale na obstojnost betonov SCC, v okviru razvojno-raziskovalne naloge DARS z naslovom Uporaba samozgoščevalnih betonov za povečanje trajnosti betonskih varnostnih ograj. V okviru obeh razvojnih projektov so bile obravnavane predvsem možnosti uporabe betona SCC pri konstrukcijah z gosto armaturo in pri elementih, kjer je kakovost vgradnje ključnega pomena za trajnost konstrukcije. Dokaz aplikativne vrednosti razvitih mešanic je bila izdelava elementa betonske varnostne ograje New Jersey, v obratu podjetja Primorje v Ajdovščini [1,2], ki je recepturo ekonomičnega betona SCC v prihodnjih letih modificiralo in uporabilo za gradnjo stavb in različne infrastrukture [3].

Po končanih razvojno-raziskovalnih projektih za DARS so se raziskave razširile in poglobile v okviru številnih zaključnih del na vseh treh stopnjah študija – dodiplomski, magistrski in doktorski – ter v okviru aplikativnih in razvojnih projektov za industrijske partnerje [4-6]. Od leta 2011 naprej temelji razvoj novih sestav betonov SCC na meritvah reoloških lastnosti svežih mešanic, z opremo ConTec Viscometer 5.

Takšen raziskovalni pristop, ki je neprekinjeno trajal okrog 20 let, je omogočil sistematično obravnavo vseh ključnih vidikov SCC, od zasnove sestave in reologije svežega betona do mehanskih in trajnostnih lastnosti v strjenem stanju ter validacije predlaganih rešitev v realnih konstrukcijah.

Posebnost raziskav SCC na UL FGG je bila od vsega začetka usmerjenost v razvoj tehnologije, prilagojene lokalno dostopnim materialom in potrebam slovenske gradbene prakse. V nasprotju z mnogimi zgodnjimi sestavami betonov SCC, razvitimi na Japonskem in pozneje v državah severne Evrope, ki so temeljile na uporabi rečnih prodov in peskov ter visokih vsebnostih cementa, smo se v raziskavah osredotočili predvsem na uporabo drobljenih karbonatnih agregatov, zlasti apnenčevih agregatov iz slovenskih kamnolomov, ter na uporabo apnenčeve moke kot polnila v pasti, s ciljem zmanjšanja količine cementa. Takšen pristop se je izkazal kot ključen za razvoj t. i. ekonomičnih sestav betonov SCC, ki poleg ustreznih reoloških in mehanskih lastnosti omogočajo tudi nižje proizvodne stroške in boljšo trajnostno naravnanost zaradi uporabe v tistem času še stranskih produktov iz kamnolomske dejavnosti (apnenčeva moka, pridobljena z odpraševanjem drobljenega agregata).

V kasnejših raziskavah smo obravnavali tudi vpliv drugih vrst agregatov, predvsem dolomitnih agregatov [7], novih vrst superplastifikatorjev (na bazi polifosfonatov) [4, 8] ter razvijali posebne sestave betonov SCC, kot so lahkoagregatni betoni SCC (LSCC) [5, 6]. Sestave LSCC odpirajo nove možnosti uporabe, zlasti na področju industrijsko izdelanih elementov ali proizvodov, kot so gotove kopalnice, enote za modularno gradnjo itd., kjer so poleg mehanskih lastnosti pomembni še zmanjšana lastna teža, izboljšana toplotna in zvočna izolativnost ter požarna odpornost, skupaj z določenimi funkcionalnimi lastnostmi (na primer površine iz brušenega betona).

Namen tega članka je predstaviti ključne raziskovalne ugotovitve na področju tehnologije betonov SCC in LSCC, do katerih smo prišli na UL FGG ter izkušnje pri prenosu razvite tehnologije v prakso, preko preverjanja rešitev na konstrukcijski elementih ali gradbenih proizvodih. Poseben poudarek je namenjen povezavi med laboratorijskimi raziskavami in industrijsko uporabo, saj prav ta vidik predstavlja eno ključnih dodanih vrednosti predstavljenega razvojno-raziskovalnega dela.

2. RAZVOJ PRVIH SESTAV BETONOV SCC

2.1 Koncept optimizacije spakiranosti agregata

Na podlagi pregleda obstoječe literature in udeležbe na ciljnem izobraževanju v Göteborgu na Švedskem leta 2000 [9], smo se odločili za pristop k projektiranju betona SCC, ki je temeljil na zagotavljanju zahtevanih reoloških lastnosti sveže mešanice z optimizacijo zrnavostne sestave agregata. Optimalna spakiranost agregatnih zrn zmanjša potrebo po prostornini paste za zagotavljanje samozgoščevalnih lastnosti. V okviru raziskav so bile analizirane različne kombinacije drobnih in grobih frakcij agregata (kremenčeva mivka 0/1, frakcije drobljenega apnenčevega agregata 0/4, 4/8 in 8/16). Optimalna zrnavostna sestava drobne frakcije je bila kombinacija 20 % mivke 0/1 in 80 % frakcije 0/4. Pri grobih frakcijah, pa je bila optimalna spakiranost delcev dosežena pri kombinaciji 40 % frakcije 4/8 in 60 % frakcije 8/16. V nadaljevanju smo, v skladu s pristopom Okamure in Ozawe [predstavljen v 9], izbrali prostornino tako sestavljenega drobnega agregata v malti enako 40 % ter prostornino tako sestavljenega grobega agregata v betonu, ki je enaka 50 % njegove prostorninske mase v zbitem stanju (50 % od 1550 kg/m^3). S tem smo določili tudi prostornino paste za beton SCC.

2.2 Optimizacija sestave paste

V začetni fazi raziskav betonov SCC je bil poudarek na razumevanju vpliva zrnavostne sestave cementa in apnenčastih polnil (skupaj tvorijo praškaste delce v sestavi) na reološke lastnosti paste, v kateri spreminjamo količino vode (Slika 1). Dva parametra, ki jo določamo s testom razleza s prisekanim stožcem na pasti [10], sta:

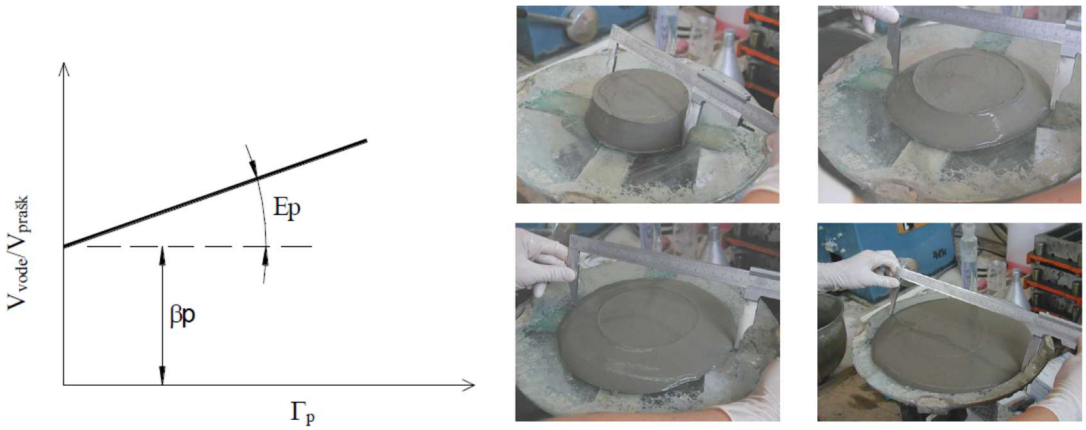
βp - koeficient zadrževanja vode, ki predstavlja razmerje $V_{vode}/V_{prašk}$, pri katerem pasta doseže »nulti razlez« (Γp=0). Prostornina vode je v tem primeru sestavljena iz vode, adsorbirane na površini praškastih delcev in vode, ki zapolnjuje votline med praškastimi delci ter omogoča zadostno dispergiranje delcev za začetno tečenje mešanice [10]. Pasta primerna za izdelavo betona SCC ima βp praviloma med 0,8 in 0,9. Nižja kot je vrednost βp, bolj praškasti delci izboljšajo sposobnost tečenja paste.

Ep – koeficient deformiranja, ki predstavlja mero odpornosti praškastih delcev proti deformiranju pri naraščanju količine vode v mešanici (ocena viskoznosti), ki je pripravljena brez kemijskih dodatkov.

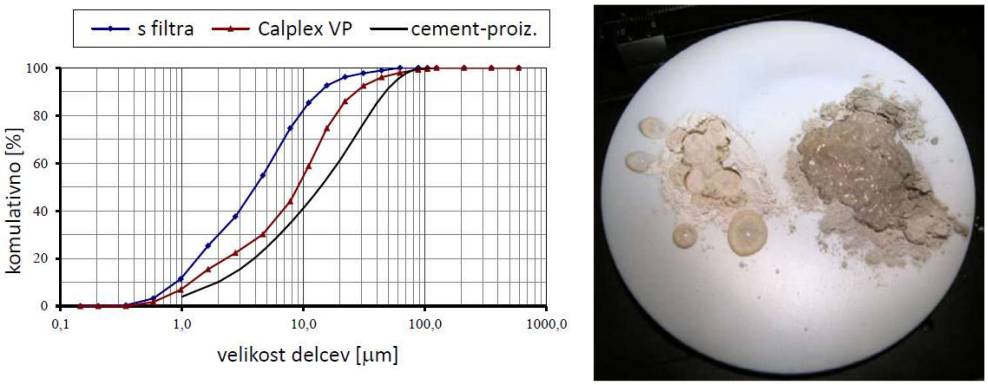
Analizirali smo dve apnenčevi moki, mleto kameno moko Calplex VP ter kameno moko s filtra iz istega kamnoloma, kot je drobljen apnenčev agregat. Razlikovali sta se predvsem po zrnavostni sestavi delcev in sposobnosti omočenja z vodo. Mleta apnenčeva moka je bila bolj groba, hkrati pa je bila površina njenih delcev hidrofobna (Slika 2).

Rezultati preiskav past z razlezom [10] so pokazali (Slika 3), da je koeficient zadrževanja vode βp odvisen predvsem od deleža apnenčeve moke v sestavi paste in doseže vrednost manjšo od 0,9 pri 50 % prostorninskem deležu kamene moke v sestavi praškastih delcev. Vrsta apnenčeve moke pa vpliva predvsem na koeficient deformiranja Ep, pri čemer moka s filtra z naraščanjem količine vode izboljša sposobnost deformiranja paste, v primerjavi z mleto apnenčevo moko.

Koeficient zadrževanja vode βp pri sestavi praškastih delcev 50 %vol cementa in 50 %vol apnenčeve moke je določil količino vode v pasti in pozneje tudi v betonu. Na taki sestavi paste smo v nadaljevanju analizirali učinkovitost različnih superplastifikatorjev PCE (SP PCE), ki so bili dostopni na trgu. Rezultati za sestavo z mleto apnenčevo moko so prikazani na Sliki 4.



Slika 1: Določitev reoloških parametrov βp in Ep za optimizacijo sestave paste SCC.



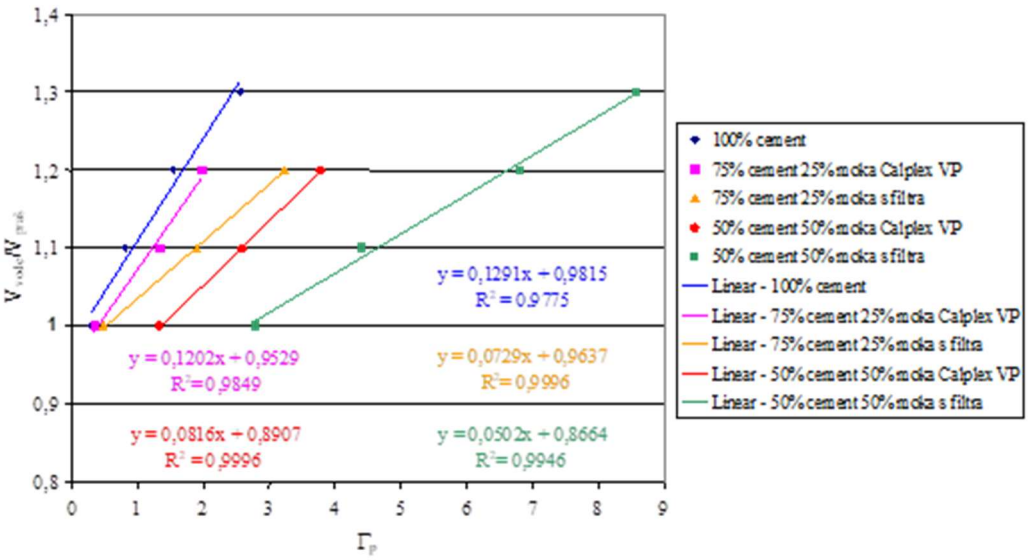
Slika 2: Lastnosti mlete apnenčeve moke in apnenčeve moke s filtra.

Izbira vrste in količine SP PCE za nadaljnje preiskave ni temeljila samo na rezultatih razleza paste takoj po zamešanju, ampak predvsem na njegovi sposobnosti vzdrževanja razleza s časom v določenih mejah.

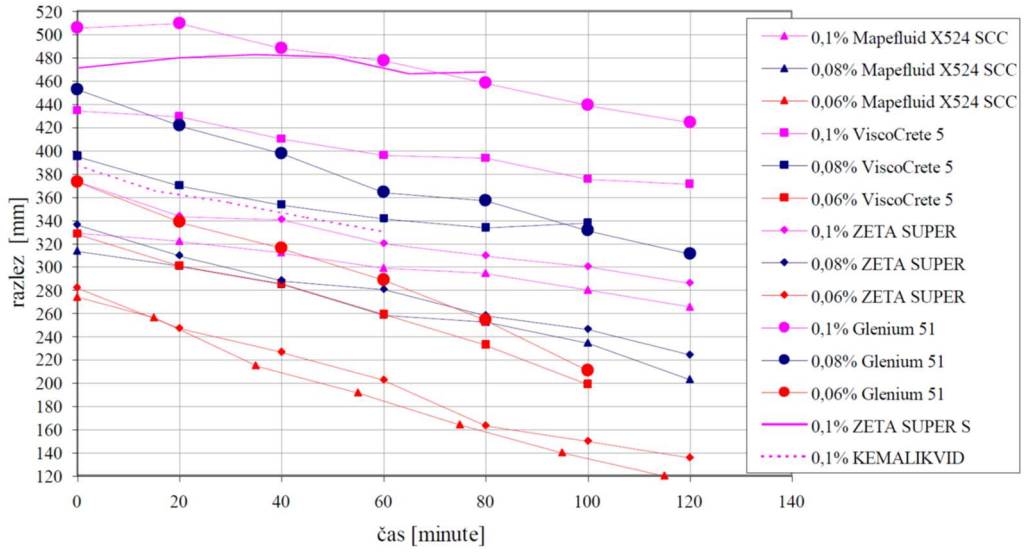
2.3 Preiskave na maltah in betonih

V nadaljevanju so potekale še preiskave na maltah. Analizirali smo vpliv količine treh izbranih SP PCE na razlez malte [10] in njeno iztekanje iz V-lijaka za čase 0, 30 in 60 minut po zamešanju. Preiskave so pokazale, da so izbrani superplastifikatorji (Mapefluid X524 SCC, Cementol Zeta Super S in Glenium 51) primerni za izdelavo betonov SCC. Zato smo jih uporabili za pripravo različnih sestav SCC, pri katerih smo spreminjali vrsto apnenčeve moke ter sestavo drobne frakcije agregata (z ali brez kremenčeve mivke). Ugotovili smo namreč, da kombinacija kremenčeve mivke in apnenčevega drobljenega agregata lahko predstavlja težavo pri zagotavljanju dolgoročne obstojnosti betonov SCC. Poleg tega pa ima izključitev kremenčeve mivke iz sestave za proizvajalca betona SCC praviloma tudi ekonomsko korist.

Merila glede izpolnjevanja samozgoščevalnih lastnosti so bila na začetku naših preiskav naslednja: razlez s posedom ≥ 700 mm in homogena površina razlitega vzorca; čas iztekanja iz V-lijaka med 4 in 15 sekundami; razlez s posedom skozi Japonski obroč ≥ 700 mm, na ovirah ni blokiranja; blokirno razmerje pri



Slika 3: Način določitve reoloških parametrov βp in Ep za različne kombinacije deležev apnenčeve moke in cementa v pasti.



Slika 4: Rezultati razleza pri študiji vpliva vrste in deleža SP PCE na reološke lastnosti paste.

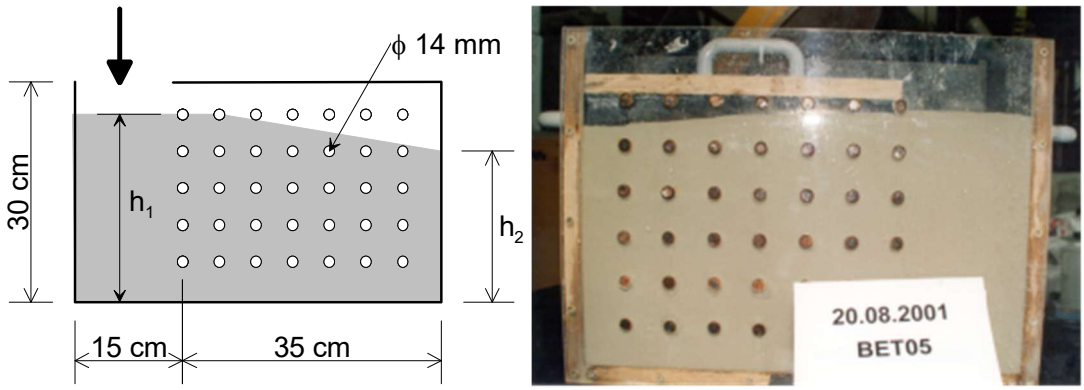
L-zaboju > 0,8, zapolnitveno razmerje F pri škatli Kajima ≥ 90% ($F=(h_1+h_2)/2h_1 \cdot 100$). Poudariti je treba, da takrat za betone SCC še ni bilo na voljo standardov ali splošno sprejetih smernic. Na Sliki 5 je prikazan preskus s škatlo Kajima, ki se pozneje ni uveljavil kot standardna preskusna metoda, zaradi velike količine betonskega vzorca.

Parametri betonov SCC, ki so izpolnjevali postavljena merila, so se gibali v naslednjih mejah: prostornina paste med 0,41 in 0,43 m^3; razmerje med prostornino vode in praškastih delcev med 0,63 in 0,73; delež grobega agregata med 0,280 in 0,294 m^3; vodo-cementno razmerje med 0,42 in 0,48; masa cementa med 372 in 386 kg. Z vgradnjo dveh izbranih sestav betonov v konstrukcijske elemente v laboratoriju, AB nosilec in AB steno (Slika 6), smo preverili še sposobnost tečenja in sposobnost zapolnjevanja betonov SCC ter zagotavljanje homogenih lastnosti v strjenem stanju v celotnem elementu.

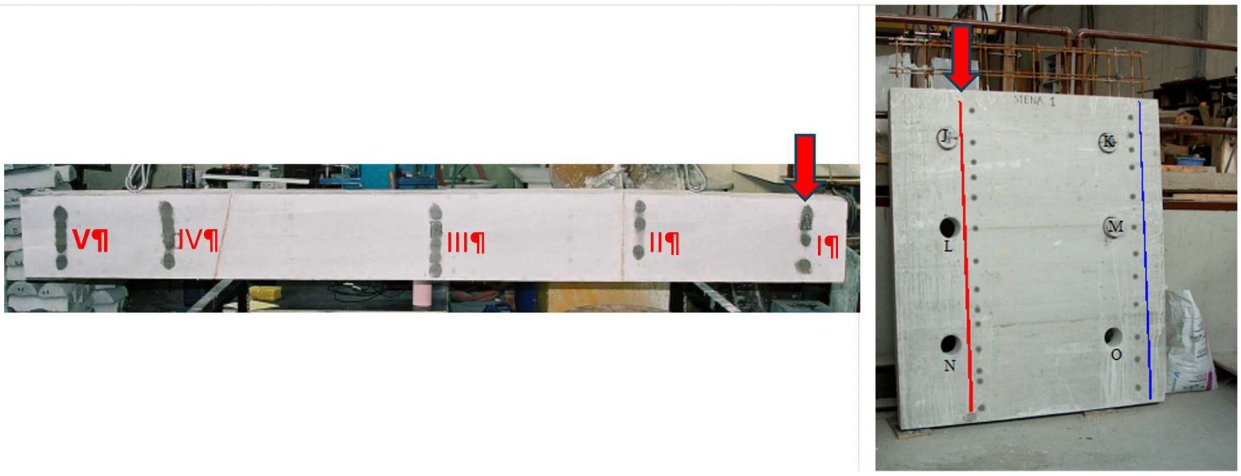
Koeficient variacije dinamičnega modula elastičnosti vzdolž AB nosilca, pri katerem smo beton vgrajevali na desnem robu s pomočjo posode za beton (linija I na Sliki 6 levo), je bil na vseh petih pozicijah opravljenih meritev (I do V) manjši od 5 %. Beton SCC smo v opaž AB stene vgrajevali kontraktorsko, vzdolž leve, rdeče linije (Slika 6 desno). Najdaljšo pot tečenja, kjer so bile opravljene meritve, predstavlja modra linija. Koeficient variacije rezultatov meritev v vertikali kontraktorskega vgrajevanja je bil 4,0 %, v vertikali največje poti tečenja pa 6,7 %.

3. OBSTOJNOST BETONOV SCC

V naslednji fazi raziskav, ki so bile izvedene v okviru druge razvojno-raziskovalne naloge, ki jo je financiral DARS [2] in doktorske disertacije Davida Duha [11], smo se osredotočili na preiskave obstojnosti betonov SCC različnih sestav. Pri sestavah z drobljenim apnenčevim agregatom smo vzporedno analizirali tudi vibriran beton z enakim v/c razmerjem in količino



Slika 5: Preiskava s škatlo Kajima.

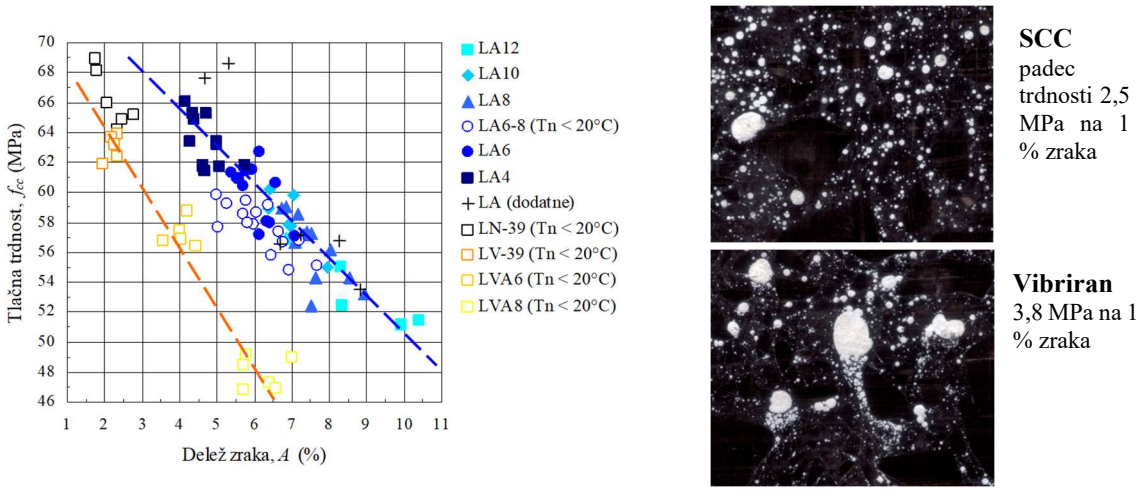


Slika 6: AB nosilec po preiskavah z ultrazvokom (levo) in AB stena po preiskavah z ultrazvokom in izvrtanju valjev (desno).

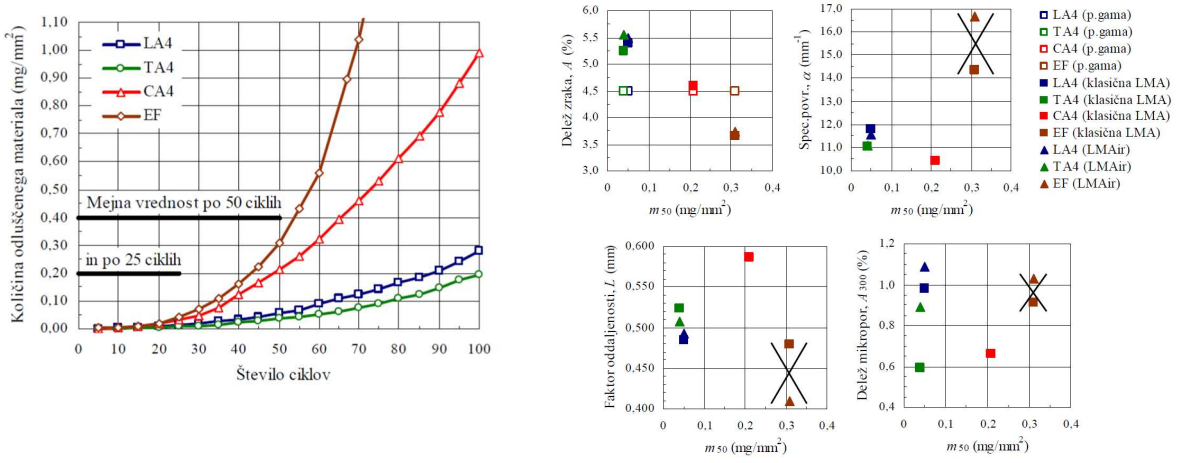
cementa ter vrsto in zrnavostno sestavo drobnega in grobega agregata.

Rezultati tlačnih trdnosti pri starosti 28 dni so za sestave z v/c razmerjem 0,39 in različnimi deleži zraka (številke 4, 6, 8, 10 in 12 predstavljajo % zraka v betonu) predstavljeni na Sliki 7. L pomeni beton SCC iz drobljenega apnenčevega agregata in moke s filtra, črka A pove, da je beton aeriran, oznaka LV pa označuje vzporedno sestavo vibriranega betona (k L) brez moke. Iz rezultatov na Sliki 7 lahko vidimo, da dosegajo betoni SCC pri starosti 28 dni višje tlačne trdnosti, kot primerljivi vibrirani betoni in da se razlika v tlačnih trdnostih veča z večanjem deleža vnesenega zraka v betonu. Razlogi za to so bolj enakomerna porazdelitev in manjši premeri zračnih mehurčkov pri betonih SCC ter odsotnost bolj poroznega stičnega območja med agregatnimi zrni in vezivno pasto, zaradi izločenega vibriranja.

Na izbranih sestavah smo v nadaljevanju preverjali odpornost betona proti zmrzovanju in tajanju v prisotnosti talilnih soli, v skladu s SIST 1026 [12]. Pri tem smo spreminjali tudi trajanje mokre nege in temperaturo vode. Na Sliki 8 prikazujemo rezultate preiskav na sestavah s projektiranim deležem zračnih mehurčkov 4 %, skupaj s karakteristikami zračnih por za posamezno sestavo, ki jo je dala linijska mikroskopska analiza (LMA). Črka L pomeni beton SCC iz drobljenega apnenčevega agregata in moke s filtra, črka T označuje beton SCC iz rečnega proda in kremenčeve mivke, črka C beton SCC z moko pridobljeno z mletjem apnenca, oznaka EF pa sestavo s filtrskim pepelom namesto apnenčeve moke. Črka A



Slika 7: Tlačna trdnost vibriranih betonov in betonov SCC z različno vsebnostjo zračnih por (levo) ter mikroskopska slika porazdelitve zračnih por in mikropor v vibriranem betonu in betonu SCC (desno) [11].



Slika 8: Odpornost različnih sestav betonov SCC s 4 % zraka, proti zmrzovanju in tajanju v prisotnosti talilnih soli [11].

pove, da je beton aeriran. Ugotovili smo, da LMA ni primerna za analizo betonov s filtrskim pepelom, če nam ne uspe ločiti por, ki so posledica votlih kroglastih delcev pepela v dimnih plinih. Rezultati kažejo tudi na drugačno kakovost zračnih mehurčkov v pasti z moko s filtra (LA), v primerjavi s pasto z mleto apnenčevo moko (CA). Čeprav je bilo za doseganje enake količine zraka pri sestavi CA treba dodati več aeranta, pa je kakovost zračnih por v sestavi betona CA slabša, kar potrjujejo manjša specifična površina, večji faktor oddaljenosti ter manjši delež mikropor. To pomeni, da tudi vrsta uporabljene apnenčeve moke pomembno vpliva na karakteristike sistema zračnih mehurčkov v strjenem aeriranem betonu.

4. LAHKOAGREGATNI BETONI SCC

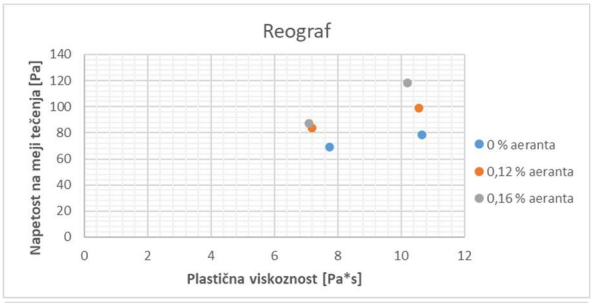
Zasnovo lahkoagregatnega betona SCC (LSCC) z največjim zrnom D_{max} 8 mm je omogočil reometer ConTec Viscometer 5, saj je bilo treba zasnovati pasto z drugačnimi reološkimi lastnostmi, kot pri betonih iz drobljenega apnenčevega agregata, da se prepreči segregacija zrn lahkega agregata proti površini mešanice in istočasno zagotovi visoka sposobnost tečenja. Zato smo vpliv različnih parametrov, kot so delež zraka, delež apnenčeve moke, delež gostilca, itd. študirali s pomočjo reoloških preiskav, katerih rezultate smo prikazali v obliki reografa (Slika 9). Za vsak parameter imamo dva rezultata, prvega takoj po zamešanju in drugega po 30 minutah po zamešanju. Za sestave, pri katerih je bil razlez s posedom takoj po zamešanju v območju 650±50 mm, se napetosti na meji tečenja za betone LSCC gibljejo med 50 in 80 Pa, plastična viskoznost pa med 5 in 10 Pa·s. Primerjava z betonom SCC iz drobljenega agregata in apnenčeve moke, ki dosega razlez s posedom v enakem območju pokaže, da pri uporabi SP PCE dosegamo napetost na meji tečenja okrog 24 Pa, plastično viskoznost pri nizkih rotacijah 29 Pa·s, pri višjih rotacijah pa 45 Pa·s. To pomeni, da pri LSCC stabilnost mešanice dosegamo z višjo napetostjo na meji tečenja.

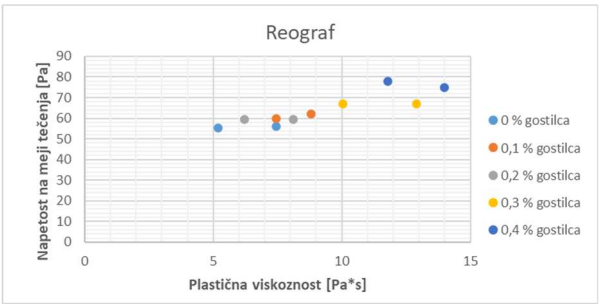
Pri betonih LSCC je najbolj zahtevno obvladovanje vlažnosti visokoporoznega agregata, da se prepreči hiter odvzem vode iz paste in s tem izguba samozgoščevalnih lastnosti. V strjenem stanju je njihova prednost nizka lastna teža (manj kot 1600 kg/m^3) in za 40 % nižja toplotna prevodnost (manj kot 1 W/mK). Hkrati predstavljajo porozna zrna lahkega agregata zalogovnik vlage in s tem omogočajo notranjo nego betona.

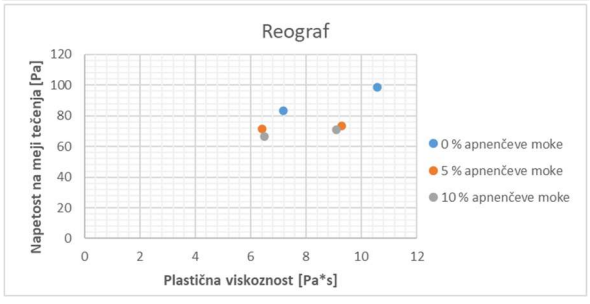
6. SKLEP IN POGLED V PRIHODNOST

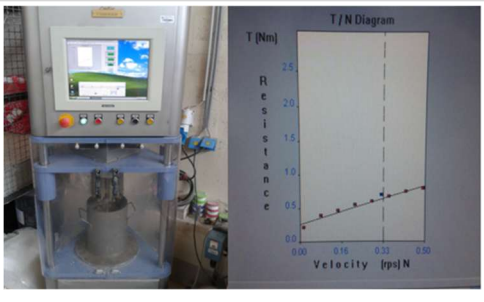
Razvoj betonov SCC na UL FGG predstavlja primer dolgoročnega in sistematičnega raziskovalnega dela, pri katerem so bile laboratorijske raziskave neposredno povezane z reševanjem praktičnih izzivov v gradbeništvu. Raziskave, ki so se začele leta 1999 v okviru razvojno-raziskovalnih projektov za DARS, so omogočile razvoj prvih ekonomičnih sestav betonov SCC iz lokalno dostopnih drobljenih apnenčevih agregatov in apnenčeve moke s filtra. Takšen pristop je bil v tistem času razmeroma inovativen, saj so prve tuje sestave betonov SCC praviloma temeljile na uporabi rečnih agregatov in visokih količin cementa, rešitve v Sloveniji (na primer, v takratnem podjetju ABK-INTERNATIONAL v Šempetru pri Novi Gorici) pa so bile vpeljane s strani tujih proizvajalcev kemijskih dodatkov za beton SCC.

Ključna dodana vrednost raziskav UL FGG je bila povezava med temeljnim razumevanjem reološkega obnašanja cementnih past, malt in betonov SCC ter preverjanjem delovanja razvitih sestav na









Slika 9: Reografi za različne sestave betonov LSCC.

konstrukcijskih elementih in v realnih proizvodnih pogojih. Rezultati preiskav so pokazali, da je mogoče z optimizacijo zrnavostne sestave agregata, ustreznim deležem praškastih delcev ter pravilno izbiro superplastifikatorja razviti robustno sestavo SCC z dobro sposobnostjo tečenja, visoko odpornostjo proti segregaciji ter izboljšanimi mehanskimi lastnostmi in obstojnostjo.

Posebej pomembne so bile raziskave obstojnosti betonov SCC, saj so pokazale, da lahko pravilno zasnovan beton SCC dosega bolj homogeno mikrostrukturo, boljšo porazdelitev zračnih por in večjo odpornost proti delovanju zmrzovanja in tajanja kot primerljivi vibriran beton. Kasnejši razvoj lahkoagregatnih betonov SCC (LSCC) pa je odprl nove možnosti uporabe tehnologije na področju lahkih industrijsko izdelanih elementov, modularne gradnje in drugih gradbenih proizvodov z izboljšano toplotno in zvočno izolativnostjo.

Uporaba betonov SCC v sodobnem gradbeništvu ni več le tehnološka alternativa klasičnim vibriranim betonom, temveč postaja nujnost pri izvedbi zahtevnih armiranobetonskih konstrukcij. To velja predvsem za potresno odporno gradnjo, kjer sodobni pristopi projektiranja vitkih elementov in/ali elementov kompleksnih geometrij zahtevajo velik odstotek jeklene armature v betonskem prerezu. V takšnih primerih je zanesljivo zapolnjevanje opaža in popolno oblitje armaturnih palic mogoče zagotoviti le z uporabo betonov SCC.

Pomemben potencial imajo betoni SCC tudi v prihajajoči avtomatizaciji in robotizaciji gradbeništva. Zaradi visoke sposobnosti tečenja in zapolnjevanja ter izločenega vibriranja so betoni SCC posebej primerni za integracijo v digitalizirane in avtomatizirane proizvodne procese. Ena izmed obetavnih smeri razvoja je uporaba robotskih sistemov za 3D tisk opažev kompleksnih oblik, ki jim sledi avtomatizirano nameščanje armaturnih košev in zapolnjevanje opažev z betonom SCC (Slika 10). Takšni pristopi omogočajo večjo svobodo oblikovanja, optimizacijo porabe materialov ter zmanjšanje potrebe po ročnem delu na gradbišču.

Prihodnji razvoj tehnologije betonov SCC bo zato tesno povezan z razvojem digitalnega projektiranja, robotizirane proizvodnje in trajnostnega gradbeništva. V tem kontekstu predstavljajo izkušnje, pridobljene v okviru raziskav UL FGG, pomembno osnovo za nadaljnji razvoj naprednih betonskih tehnologij in njihovo uporabo v prihodnjih generacijah trajnostnih in digitaliziranih konstrukcij.

Betoni SCC tako predstavljajo pomemben most med klasično tehnologijo betona in prihodnjimi digitaliziranimi, trajnostnimi ter avtomatiziranimi procesi gradnje.

ZAHVALA

Zahvaliti se želim vsem svojim diplomantom, magistrantom in doktorandom, ki so s sodelovanjem pri laboratorijskih raziskavah prispevali k razvoju betonov SCC na UL FGG. To so: David Duh, Andraž Hočevar, Jure Klopčič, Jože Maver, Karmen Jazbec, Aleš Miketič, Nejc Gašperič, Maša Kušar, Goran Šneperger, Mitja Žnidaršič, Lovro Cimperman, Barbara Pezdirc, Franc Turk, Jože Mehle, Uroš Vetrih, Jure Trtnik, Damjan Lampe, Klavdija Lampret, Igor Cerovšek, Sandra Petan, Jure Nedelko, Vid Pristavec, Neža Gošte, Danijel Benko.



Slika 10: Nosilec iz betona SCC v klasičnem opažu in opažu, natisnjenem s tehnologijo 3D tiska (levo – foto Jan Panič), z robotsko roko (desno).

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33. SLOVENSKI KOLOKVIJ O BETONIH

Experiences and Limitations in the use of SCC

Izkušnje in omejitve pri uporabi SCC

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HOLCIM Zementwerke GmbH - Vienna

Abstract

Self-compacting concrete (SCC) offers clear execution and quality benefits where conventional compaction is difficult, notably in precast elements, architecturally exposed surfaces, and heavily reinforced structural members. This paper summarises practical experiences with SCC and highlights limitations that frequently govern successful application: the tight balance between flowability, viscosity and segregation resistance; sensitivity to material variability and time-dependent rheology; and the strong influence of admixture–binder interactions on robustness. Beyond fresh-performance requirements and test methods, the paper emphasises production and placing controls (moisture correction, mixing energy, transport time, re-dosing rules, and discharge strategy) as decisive for repeatable filling and surface quality. Particular attention is given to risks associated with powder-rich SCC designs, including elevated heat of hydration, high member temperatures and early-age cracking, and to situations where very high reinforcement density can still cause blocking or incomplete filling. The conclusions stress that SCC is not a "magic fluid" but a performance-based system that requires clear acceptance criteria, fast feedback loops and disciplined execution to achieve durable, reproducible structural concrete.

Povzetek

Samozgoščevalni beton (SCC) ponuja očitne prednosti pri izvedbi in kakovosti tam, kjer je običajno zgoščevanje težavno, zlasti pri prefabriciranih elementih, arhitekturno izpostavljenih površinah in močno armiranih konstrukcijskih elementih. V tem članku so povzete praktične izkušnje v zvezi s SCC ter poudarjene omejitve, ki pogosto vplivajo na uspešno uporabo: občutljivo ravnovesje med pretočnostjo, viskoznostjo in odpornostjo proti segregaciji; občutljivost na razlike v materialu in časovno odvisno reologijo; ter močan vpliv medsebojnega delovanja dodatkov in veziva na robusnost. Poleg zahtev za obnašanje v svežem stanju in preskusnih metod članek izpostavlja nadzor proizvodnje in vgradnje (popravljanje vlage, energija mešanja, čas transporta, pravila za ponovno doziranje in strategija praznjenja) kot odločilne dejavnike za ponovljivo polnjenje in kakovost površine. Posebna pozornost je namenjena tveganjem, povezanim z visoko vsebnostjo praškastih delcev v sestavi SCC, vključno s povečano toploto hidratacije, visokimi temperaturami elementov in zgodnjim razpokanjem, ter situacijam, v katerih lahko zelo visoka gostota armature kljub temu povzroči blokiranje ali nepopolno zapolnitev. V zaključkih je poudarjeno, da SCC ni »čudežna tekočina«, temveč sistem, ki temelji na zmogljivosti in za doseganje trajnega, ponovljivo izdelanega konstrukcijskega betona zahteva jasna merila sprejemljivosti, hitre povratne zanke in disciplinirano izvedbo.

Keywords: rheology; segregation resistance; quality control; early-age cracking, easy compacting concrete, experience

Ključne besede: reologija; odpornost proti segregaciji; nadzor kakovosti; zgodnje razpokanje, lahko zgostljiv beton, izkušnje

1. INTRODUCTION: APPLICATIONS AND PRACTICAL CHALLENGES IN PRODUCING SCC STRUCTURAL MEMBERS N

Self-compacting concrete (SCC) is a concrete that flows, deaerates and completely fills the formwork and reinforcement spaces solely under gravity, without external compaction (vibration). SCC therefore addresses key weaknesses of conventional concreting, such as inadequate compaction in heavily reinforced zones, complex formwork geometries, or restricted access, and the resulting defects (e.g., voids, honeycombing, and gravel pockets). Typical fields of application include the precast industry (repeatability and surface quality), architectural/exposed concrete,

members with high reinforcement congestion (e.g., column–beam joints, shear walls, deep beams), repair and infill concreting, and specialised applications in infrastructure and tunnel construction.

However, the benefits of SCC depend on a narrow balance of rheological properties: a sufficiently low yield stress (to ensure flow spread and passing ability) combined with sufficient plastic viscosity and robustness against segregation and sedimentation (to maintain homogeneous grading, consistent air content where relevant, and reproducible surface finish). In practice, this leads to specific challenges: (i) high sensitivity to variations in constituent materials (aggregate moisture and grading, fines content, cement batch variability), (ii) time-dependent consistency changes (setting behaviour, workability retention, and possible delayed dispersion effects of superplasticisers), (iii) interactions between superplasticisers and supplementary cementitious materials (e.g., fly ash, limestone filler, silica fume), (iv) increased demands on mixing, transport and placing operations (homogeneity and control of shear history), and (v) the risk of side effects from mix designs optimised primarily for flow (e.g., increased heat of hydration at high cement/binder contents, plastic shrinkage, and early-age cracking susceptibility).

For design, specification, production and execution, SCC-specific requirements are detailed in guidelines and technical recommendations. In Austria, the Austrian Society for Construction Technology (ÖBV) guideline on self- and lightly compacting concrete (SCC/ECC) is commonly used as a key reference. Across Europe, the "European Guidelines for Self-Compacting Concrete" (EFNARC/EPG) are frequently adopted as the state of practice. In addition, national rules and technical bulletins exist in the German-speaking countries, particularly addressing fresh concrete testing and robustness. Where a project- or client-specific document (e.g., an internal "Opelvor" guideline/specification for SCC) applies, its provisions (target values, tolerances, testing and documentation requirements) should be incorporated into the concrete specification and the site quality plan as the governing requirement level.

2 MATERIAL CONCEPT AND MIX DESIGN

2.1 Rheological fundamentals

The self-compacting behaviour results from targeted control of fresh concrete rheology. In practice, SCC is often described using two complementary indicators: (1) flowability (slump-flow spread) as an indicator of low yield stress and (2) viscosity/flow resistance (e.g., T500 time, funnel discharge time) as an indicator of stability and controlled flow rate. The objective is a combination that reliably provides filling ability and passing ability while minimising segregation, sedimentation and bleeding. Because SCC is placed without vibration, air release must occur through the flow process itself; this requires a robust, non-blocking mix design and an appropriate placing concept (e.g., suitable discharge points, limited free-fall heights, and—where relevant—a placing concept).

2.2 SCC types and the role of powder content

In the literature, SCC mixes are often classified according to the stabilisation concept: powder-type mixes (stability primarily achieved through increased powder/binder content), viscosity-modifying type mixes (use of viscosity-modifying admixtures, VMA), and combined concepts. The powder content (sum of cement plus fine mineral additions/fillers) is central to SCC because it increases mortar volume, improves particle packing, reduces inter-particle friction of coarse aggregate and thereby promotes flow without blocking. At the same time, high powder—and in particular high cement—contents tend to increase heat of hydration and may raise the risk of thermally induced early-age distress (see Chapter 4).

2.3 Constituents and admixture system

SCC performance is typically achieved through the interaction of (i) high-performance superplasticisers (commonly polycarboxylate ethers, PCE), (ii) an appropriate aggregate grading (often with reduced coarse aggregate content and increased mortar volume), and (iii) a tailored fine powder/binder system. Fine mineral additions such as limestone filler, fly ash or silica fume can improve flow and stability, but they also affect water demand, setting, and strength development. Viscosity-modifying admixtures (VMA) are used to improve segregation resistance, particularly for pumpable SCC or mixes with comparatively low powder content. From a production standpoint, robustness is critical: an SCC mix should tolerate small deviations in water content, aggregate moisture, or admixture dosage without either "tipping" into blocking/high viscosity or becoming unstable (segregation, sedimentation, bleeding).

3 REQUIREMENTS, TESTING AND QUALITY CONTROL

3.1 Standards and guideline framework

SCC is generally specified within the framework of EN 206 and the relevant national application documents; SCC-specific provisions are added through guidelines and project specifications. For European practice, the "European Guidelines for Self-Compacting Concrete" (EFNARC/EPG) are particularly important, as they define fresh SCC requirements (flowability, viscosity, passing ability, segregation resistance) and provide recommendations for production, transport, placing, and surface finish. In Austria, the ÖBV guideline for self- and lightly compacting concrete (SCC/ECC) is a key reference for specification and execution. Project- or client-specific documents (e.g., internal "Opelvor" requirements) may impose tighter tolerances, additional tests or documentation obligations and, where contractually binding, must take precedence in the project quality plan.

3.2 Fresh SCC performance requirements and typical test methods

Testing of SCC focuses on four performance criteria: (1) filling ability, (2) passing ability (flow through reinforcement/obstacles), (3) segregation resistance (stability), and (4) viscosity (flow rate as an indicator of stability and placeability). Depending on the applicable guideline and project specification, common test methods include:

- Slump flow including T500 time: spread diameter as a measure of flowability, T500 as an indicator of viscosity.
- V-funnel flow time: assessment of viscosity/flow rate and, indirectly, stability.
- L-box / J-ring / box test: assessment of passing ability and blocking tendency through obstacles.
- Sieve stability / segregation and settlement tests: assessment of resistance to segregation and sedimentation (visual and/or index-based).
- Air content / density / temperature: supporting indicators for repeatability, durability (where air-entrainment is specified), and robustness.

3.3 Testing and supervision concept (initial testing, identity testing, conformity assessment)

A practical quality concept combines laboratory qualification and site acceptance testing. During initial testing (mix qualification), a robust workability window is established by defining target values and tolerances (e.g., slump-flow spread and a viscosity indicator), while also verifying stability and passing ability. During identity/acceptance testing on site, the fresh SCC properties that are critical for execution are checked per delivery or at a defined frequency (e.g., slump flow including T500; supplemented by J-ring/L-box or V-funnel as required by the specification). Conformity assessment typically includes hardened concrete properties (primarily compressive strength) and full production documentation. For SCC, fast feedback loops are essential: deviations (e.g., due to

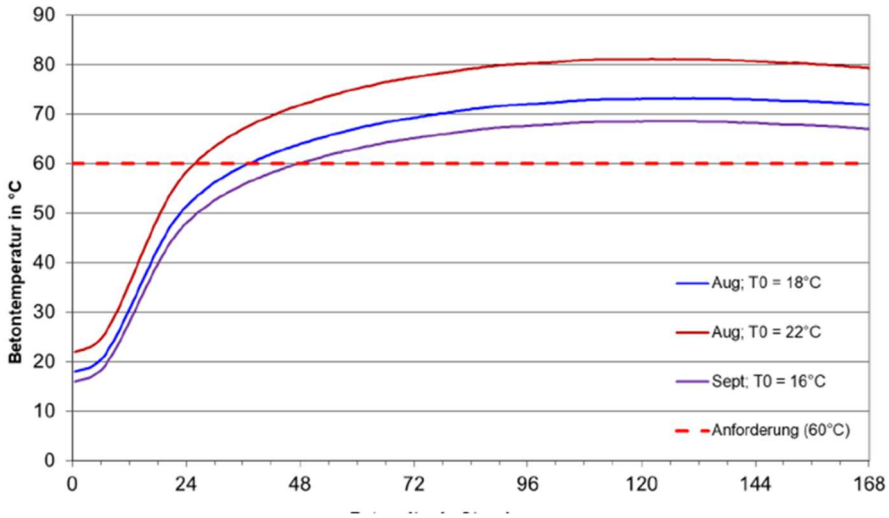


Fig 1: High concrete temperature.

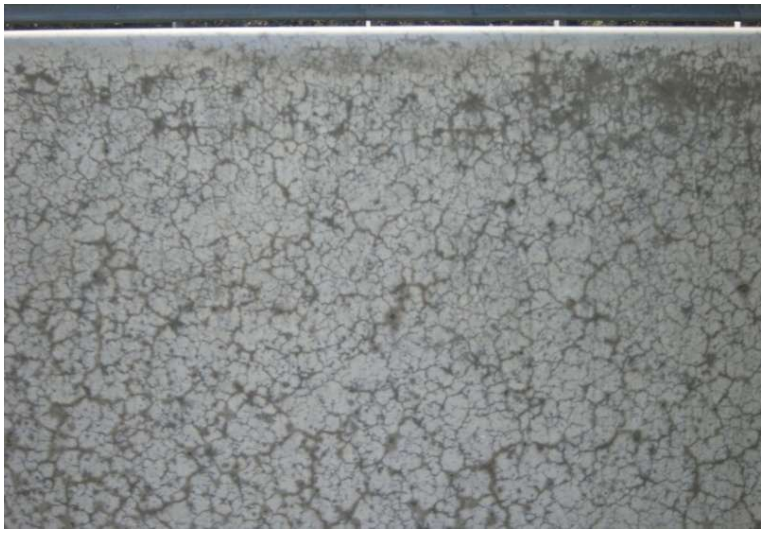


Fig 2: Early-age cracking or elephant skin

aggregate moisture variability) must be handled through predefined corrective measures (water and/or admixture adjustment within permitted limits, defined remixing times, and—where necessary—rejection of non-conforming batches). Clear responsibilities between producer, site supervision and placing crew are particularly important because even small deviations can significantly affect pouring and surface quality.

4 PRODUCTION, PLACING AND SPECIFIC RISKS

4.1 Production and placing: practical aspects

With SCC, the "quality of compaction" is effectively transferred to mix design, production consistency and placing logistics. For production, stable dosing, sufficient mixing energy/time (to fully disperse the superplasticiser) and rigorous aggregate moisture correction are decisive. For ready-mixed SCC, time-dependent workability loss must be anticipated; any on-site adjustments (e.g., superplasticiser re-dosing) are only permissible within the approved project rules and must be documented. During pumping, pressure losses, temperature and shear history can alter rheology and stability. Placing should generally limit flow distances and free-fall heights; for large members, several discharge points may be required to avoid segregation, entrapped air and non-uniform surface finish. Curing remains essential despite the lack of vibration (protection from early moisture loss and temperature control), especially for high-binder SCC and members with large exposed surfaces.

4.2 High cement/binder contents: heat of hydration, member temperatures and early-age strength

A practice-relevant risk—especially for powder-rich SCC mixes—is the tendency towards high cement and/or binder contents to achieve flowability and stability. This can lead to an increased heat of hydration, which, in massive members or elements with limited heat dissipation, may cause high concrete temperatures and pronounced temperature gradients between the core and the surface.

Such gradients promote thermally induced restraint stresses and thereby early-age cracking, particularly when rapid strength gain and a fast increase in elastic modulus occur simultaneously.

In addition, elevated cement content—at comparable water-to-binder ratio and favourable reaction conditions—can result in significantly increased in-situ compressive strengths. While this may appear beneficial from a structural capacity viewpoint, it can have side effects (e.g., higher stiffness, increased early-age deformation and shrinkage-related restraint, altered stripping/prestressing schedules, and a higher sensitivity to curing and temperature deviations).

Depending on member geometry and boundary conditions, risk mitigation may include: using low-heat or reduced-clinker binders where available, partial replacement of cement by suitable supplementary cementitious materials (e.g., slag, fly ash, limestone filler) while maintaining robustness, optimising aggregate grading and particle packing to reduce the required powder content, using VMA instead of increasing cement content, temperature management (cooling of constituent materials, placing sequence and rate, and—where required—embedded cooling measures for massive elements), as well as consistent curing and, where appropriate, temperature monitoring (embedded sensors) to control critical temperature differentials.

4.3 High reinforcement contents

In practice, SCC is very often used when the reinforcement density is high and the spacing between the reinforcing bars is small. In these situations, consider both the bar diameter and the clear diameter,



Fig 3: SCC is not always suitable for contractions with high reinforcement.

which is about 1.2 to 1.4 times larger than the bar diameter. The reinforcement spacers can also become an obstacle to the flow of concrete. In this case, it is particularly important to align the position of the spacers with the direction of concrete placement.

4.4 Easy compacting concrete (ECC) for slab tracks

In some ballastless track systems, the ECC must ensure a proper bond between the track bed and the sleeper body. It is important here that the concrete properly fills the space underneath the sleeper without leaving large voids. In addition, a certain level of early strength is required to allow traffic. An installation concept must be developed here. On the one hand, a concrete mix with high workability must be designed, and on the other hand, a compaction procedure using vibrators must be planned. Experience has shown that filling does not work without additional compaction energy.



Fig 4: SCC is not a magic fluid.

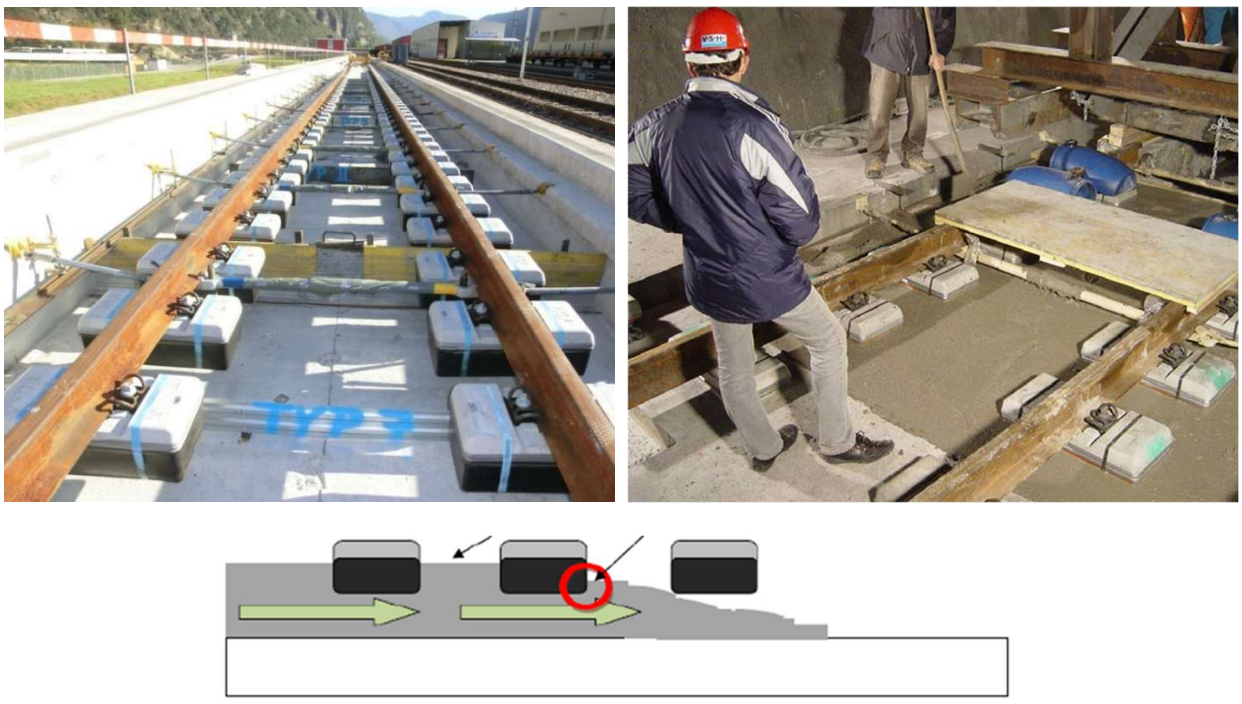


Fig 5: ECC for slab tracks

5 CONCLUSIONS

SCC enables reliable production of high-quality, void-free structural members without external vibration and offers major advantages for complex geometries, congested reinforcement and demanding surface requirements. At the same time, compared with conventional concrete, SCC requires more precise mix design, tighter production and site control, and clearly defined acceptance criteria. A key optimisation task is to avoid unnecessarily high cement/binder contents, because these increase heat of hydration and may lead to critical member temperatures, thermal restraint stresses and undesirably high early-age strengths. Current practice is supported by guidelines (e.g., ÖBV, EFNARC) and project-specific specifications; rigorous implementation in testing frequency, tolerance concept and documentation is decisive for durable and reproducible SCC or ECC construction.

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33. SLOVENSKI KOLOKVIJ O BETONIH

High-Performance Self-Compacting Cement Composites with SAP-based Internal Curing: Design and Applications

Visokozmogljivi samozgoščevalni cementni kompoziti z notranjo nego na osnovi SAP: projektiranje in aplikacije

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Abstract

High-performance cementitious composites with low water-to-binder ratios are susceptible to self-desiccation, autogenous shrinkage, and incomplete hydration, as the stoichiometric water demand of continued cement hydration exceeds the mixing water available under sealed conditions. Internal curing addresses this limitation by introducing pre-stored water reservoirs distributed uniformly within the cement matrix. This paper investigates superabsorbent polymers (SAPs) as a multifunctional component that serves simultaneously as an internal curing agent, a rheological modifier, and a carrier for photocatalytic nano-additives in high-performance self-leveling cementitious composites. The mechanically induced fragmentation of SAP hydrogel particles during mixing is discussed in relation to their effectiveness as internal curing agents. The fresh-state rheological consequences of SAP hydrogel incorporation are analyzed with respect to yield stress and plastic viscosity – properties critical for self-compacting behavior. SAP hydrogel is further examined as a dispersing medium for TiO_2 photocatalytic particles, enabling uniform distribution and enabling a fine-grained, self-leveling functional coating applied to prefabricated concrete elements. Air-purification tests conducted under conditions representative of central European urban environments demonstrate that SAP–TiO_2-modified composites achieved measurably higher NO removal efficiencies than the reference series, an effect attributed to improvements in both photocatalyst dispersion and near-surface pore connectivity. The results establish SAP hydrogel as a versatile design tool for producing durable, internally cured, and functionally tailored high-performance cementitious composites.

Povzetek

Visokozmogljivi cementni kompoziti z nizkim vodno-vezivnim razmerjem so občutljivi na samodejno izsuševanje, avtogeno krčenje in nepopolno hidratacijo, saj stehiometrična potreba po vodi za nadaljnjo hidratacijo cementa presega količino zamesne vode, ki je na voljo v zaprtih okoljih. Notranja nega odpravlja to omejitev z vgradnjo vnaprej shranjenih vodnih rezervoarjev, ki so enakomerno porazdeljeni znotraj cementne matrice. V tem članku so superabsorbentni polimeri (SAP) obravnavani kot večfunkcionalna sestavina, ki v visokozmogljivih samoizravnalnih cementnih kompozitih hkrati deluje kot notranje sredstvo za nego, reološki modifikator in nosilec fotokatalitičnih nano-aditivov. Opravljena je analiza mehansko povzročene fragmentacije delcev SAP-hidrogela med mešanjem v povezavi z njihovo učinkovitostjo kot notranjih sredstev za nego. Analizirane so reološke posledice vključitve SAP-hidrogela v svežem stanju z vidika meje elastičnosti in plastične viskoznosti – lastnosti, ki so ključne za samozgoščevalno obnašanje. SAP-hidrogel se nadalje preučuje kot disperzno sredstvo za fotokatalitične delce TiO_2, saj omogoča enakomerno porazdelitev in nanos drobnozrnatega, samoizravnalnega funkcionalnega premaza na prefabricirane betonske elemente. Testi čiščenja zraka, izvedeni v pogojih, ki so značilni za srednjeevropska urbana okolja, kažejo, da so kompoziti, modificirani s SAP–TiO_2, dosegli merljivo višjo učinkovitost odstranjevanja NO v primerjavi z referenčno serijo, kar pripisujemo izboljšavam tako pri disperziji fotokatalizatorja kot tudi pri

povezanosti por blizu površine. Rezultati potrjujejo, da je SAP-hidrogel vsestransko orodje za razvoj trajnih, notranje negovanih in funkcionalno prilagojenih visokozmogljivih cementnih kompozitov.

Keywords: cement composites, internal curing, superabsorbent polymers, SAP, high-performance

Ključne besede: cementni kompoziti, notranje negovanje, superabsorbentni polimeri SAP, visoka zmogljivost

1 INTRODUCTION

High-performance cementitious composites have become increasingly important in modern construction, owing to their high mechanical properties, enhanced durability, and reduced permeability compared with conventional concrete. These materials are routinely employed in demanding structural applications, including long-span bridges, offshore structures, nuclear containment facilities, and prefabricated elements subject to aggressive service environments. Their design is founded on the principle of maximizing packing density through low water-to-binder (w/b) ratios – typically below 0.35 – combined with high binder contents, supplementary cementitious materials (SCMs) such as silica fume and fly ash, and high-range water-reducing admixtures [1]. Although these design strategies are effective in producing dense microstructures and high compressive strengths, they simultaneously introduce a set of interrelated physicochemical challenges that compromise material integrity from the very earliest stages of hydration.

Chief among these challenges is autogenous shrinkage, which arises from chemical shrinkage – the absolute reduction in volume accompanying the hydration reaction – and the consequent self-desiccation of the capillary pore network when the external water supply is insufficient to sustain continued hydration. In systems with w/b ratios below approximately 0.40, the stoichiometric water demand for full hydration exceeds the total available mixing water, resulting in a progressive decline in internal relative humidity (RH). It was demonstrated that RH can fall below 75% in Portland cement pastes with w/b = 0.30 during the first 28 days of sealed curing, generating capillary stresses that drive autogenous deformations of 700–1000 μm/m [2]. When these deformations are restrained – as is invariably the case in structural elements – tensile stresses develop at early ages, frequently leading to micro- and macrocracking before the composite achieves its design strength [3].

Conventional external curing techniques are largely ineffective in mitigating self-desiccation within high-performance cement matrices. Low permeability, which constitutes a principal performance objective of these composites, simultaneously restricts the ingress of externally supplied water to a thin surface layer, typically not exceeding a few millimeters. This limitation is particularly severe in thin structural elements, where the high surface-area-to-volume ratio amplifies moisture gradients and renders the bulk of the composite inaccessible to external curing water.

One possible solution to these limitations is internal curing. This method involves introducing a component into the mix that can serve as distributed water reservoirs - store water, and controllably release it during cement hydration. The concept provides curing water uniformly throughout the bulk of the composite rather than solely from the surface. Several classes of materials have been investigated as internal curing agents, including pre-soaked lightweight aggregates (LWA), porous glass, and bio-based fibers [5]. Among these, superabsorbent polymers (SAPs) have emerged as particularly versatile candidates due to their exceptionally high water-absorption capacity, tunable swelling kinetics, and the ability to precisely control the volume of released water [6]. Furthermore, SAPs do not introduce pre-formed macrovoids of fixed geometry, as LWA-based agents do, but instead generate micro- and macro-pores whose size and spatial distribution can be tailored through particle size and saturation state, offering additional design flexibility [7].

The role of internal curing agents is increasingly recognized not only for shrinkage mitigation and durability improvement, but also for the design of cementitious composites with tailored functional properties. In this context, SAP may act as a multifunctional component that influences both the fresh and hardened states of the material. In fresh mixtures, SAP alters the amount of free water, thereby affecting yield stress, viscosity, flowability, and segregation resistance. After water desorption, it leaves controllable voids in the cement matrix, altering the pore-size distribution and near-surface morphology [8]. These effects are particularly relevant for self-compacting cementitious composites, in which rheological stability, casting ability, and surface quality must be achieved simultaneously. Therefore, this paper discusses SAP-based internal curing as a tool for designing high-performance self-compacting composites, with particular emphasis on thin, functionally-tailored internally cured composite layers applied to prefabricated concrete elements.

2. INTERNAL CURING OF CEMENT COMPOSITES

The thermodynamic driving force for internal curing originates in the stoichiometry of Portland cement hydration. According to the model of Powers and Brownyard, the hydration of one unit volume of anhydrous cement consumes approximately 0.253 cm^3 of chemically bound water and 0.190 cm^3 of gel water per cm^3 of cement, yielding hydration products whose absolute volume is approximately 6–8% less than the

sum of the reactant volumes. This deficit, termed chemical shrinkage, creates an equivalent volume of empty pores within the capillary network. As the hydration reaction progresses and the pore network becomes increasingly discontinuous, the internal RH falls below 100%. The resulting capillary pressure produces stresses within the pore fluid and equivalent tensile stresses in the cement matrix, manifesting as autogenous shrinkage deformations [2].

Internal curing involves introducing an additional component into the mixture that can store water and release it during hydration [9]. In contrast to external curing, which acts mainly from the surface, internal curing provides curing water in the entire volume of the cement matrix. The internal curing agent does not participate in the hydration reaction itself, but works as a distributed water reservoir - its role is to maintain internal relative humidity, reduce self-desiccation, and mainly limit the volumetric changes associated with autogenous shrinkage (Figure 1).

Internal curing agents are broadly classified according to their water storage mechanism. The first group consists of porous materials, such as saturated lightweight aggregates, porous mineral particles, or organic fillers [11]. In these modifiers, water is stored within the interconnected macro- and mesopore network of the aggregate and is released by capillary suction as the relative humidity in the surrounding cement paste declines. The second group consists of superabsorbent materials, including superabsorbent polymers. In this case, water absorption is not only a physical phenomenon, but is strongly related to the electrochemical structure of the polymer. Internal curing with SAP may therefore be more flexible from a design perspective, as the amount of absorbed water, particle size, and method of polymer introduction can be adjusted.

Superabsorbent polymers are lightly cross-linked, hydrophilic polymer networks – most commonly based on polyacrylic acid (PAA), polyacrylamide (PAM), or their copolymers – capable of absorbing and retaining water volumes many times in excess of their own dry mass [12]. Their water absorption potential results mainly from the high osmotic pressure generated by ions within the polymer structure. When SAP comes into contact with water, water molecules are absorbed into the polymer network, increasing the polymer volume and decreasing osmotic pressure. The absorption capacity of SAP depends on polymer chemistry, particle size, cross-linking density, and, importantly, the environment in which absorption occurs. In cementitious systems, the presence of ions in the pore solution and capillary pressure in the forming pore network significantly reduces the amount of water that SAP can absorb [7].

The internal curing effect of SAP is connected mainly with water desorption. During hydration, self-desiccation and internal stresses in the cement matrix disturb the equilibrium between the water stored in SAP and the surrounding cementitious environment. The rate of desorption depends on the polymer chemistry, particle size, and the magnitude of the thermodynamic driving force – i.e., the RH difference between the SAP particle and the surrounding cement matrix. Importantly, desorption is not instantaneous: larger SAP particles and those with lower cross-linking density exhibit slower release kinetics, which may prolong the internal curing effect during later-age hydration [13]. As a result, SAP gradually releases water into the cement matrix. This modifies the kinetics of water migration and influences, among others, the degree of binder hydration, mechanical properties, autogenous shrinkage, freeze–thaw resistance, and pore size distribution within the cement matrix [14-18].

SAP can be introduced into cementitious composites in different forms [19]. The most common method is adding dry, unsaturated SAP directly to the mix. In this case, SAP absorbs part of the mixing water during mixing and early hydration. Although the method is

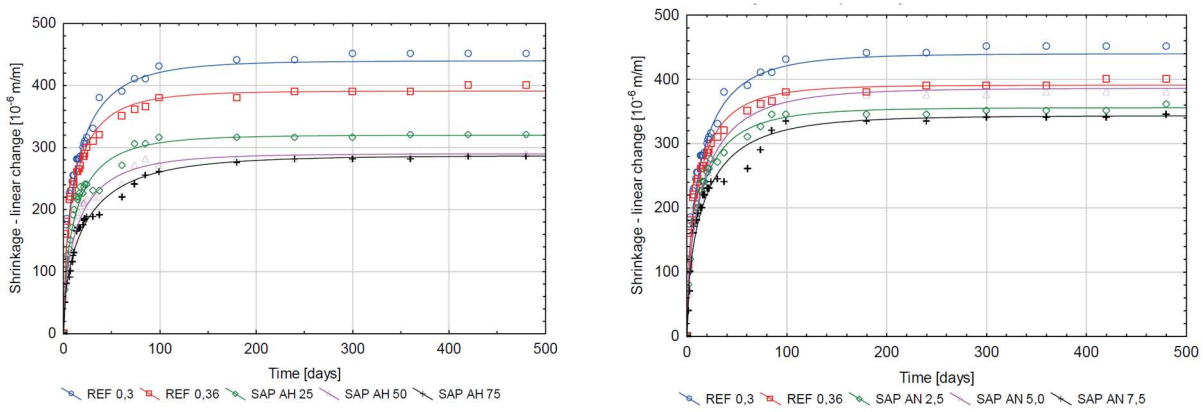
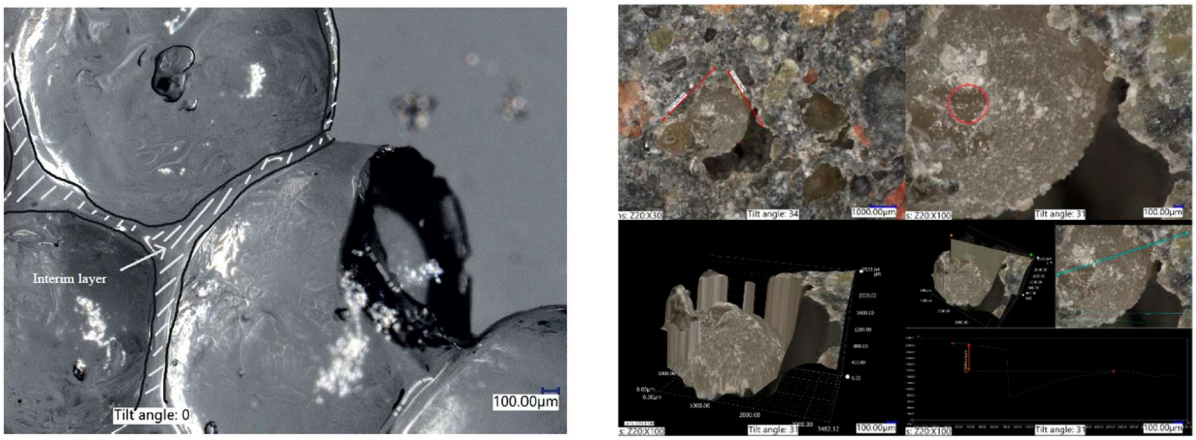


Figure 1. Aggregated test results for linear changes caused by shrinkage deformations carried out for cement composites modified with superabsorbent polymers in various variants and reference compositions; (a) SAP added as a hydrogel; (b) SAP A added in a nonsaturated state [10].

technologically simple, the absorption capacity of polyacrylic SAP in cement paste is approximately 10 times lower than in tap water [7]. Consequently, the amount of water available for internal curing is limited, while local agglomeration of SAP particles may lead to the formation of large SAP-induced pores, negatively impacting the mechanical performance of the composite (Figure 2).

An alternative method is to introduce SAP in a pre-saturated form, as a hydrogel. In this approach, the absorption stage precedes mixing, and SAP is introduced into a cementitious composite that is already saturated with water. Upon introduction into the cement paste, the direction of water transport reverses: from the beginning, water is released from the hydrogel into the cement matrix. This method increases the efficiency of internal curing, as the initial amount of water stored in SAP is higher, and desorption from SAP particles becomes the dominant mechanism controlling water availability [7]. When SAP is introduced into the cementitious mixture in a pre-saturated form, its polymer network is already expanded by absorbed water, and the osmotic pressure inside the SAP grain is reduced. In this state, as the hydrogel contains a very high water content, the polymer skeleton is stretched close to its maximum swelling capacity, making the particles more susceptible to mechanical fragmentation during mixing. The fragmentation mechanism is therefore associated with the interaction between soft, swollen SAP hydrogel particles and solid cement and aggregate grains. During mixing, friction, shear, and local impact forces generated by fine mineral particles act on the hydrogel surface, splitting the initially



(a) (b)

Figure 2. (a) The interim water layer on the outside of the water-absorbing SAP grains contributing to an increased risk of SAP grain agglomeration [10]; (b) SAP grain of spherical morphology in SAP-induced macropore within concrete volume [20].

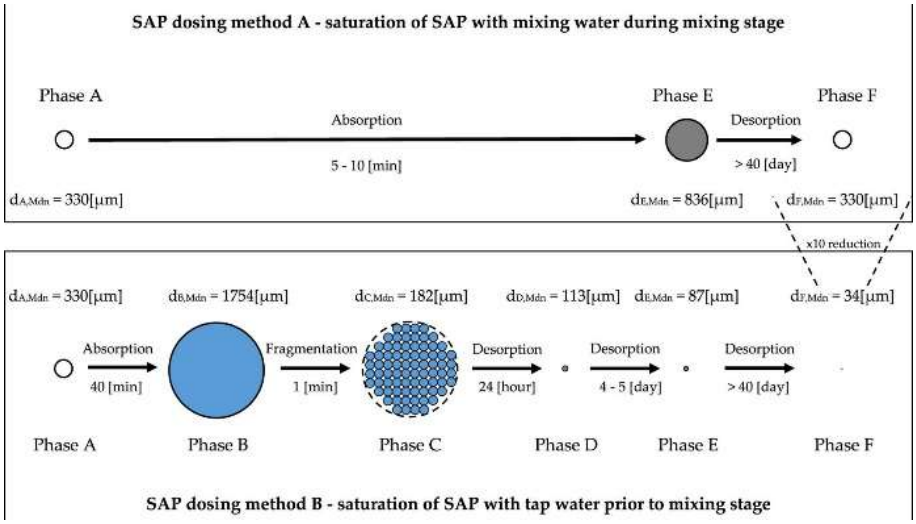


Figure 3. Particle size distribution of SAP before and after mechanical fragmentation during mixing in a cementitious environment: reduction in median particle diameter from approximately 330 µm (dry, unsaturated SAP) to approximately 34 µm (post-mixing fragments of pre-saturated SAP hydrogel), accompanied by a nearly one-order-of-magnitude increase in specific surface area [7].

swollen SAP grains into smaller fragments. After subsequent water desorption, these fragments remain as particles significantly finer than the initial dry SAP grains (Figure 3).

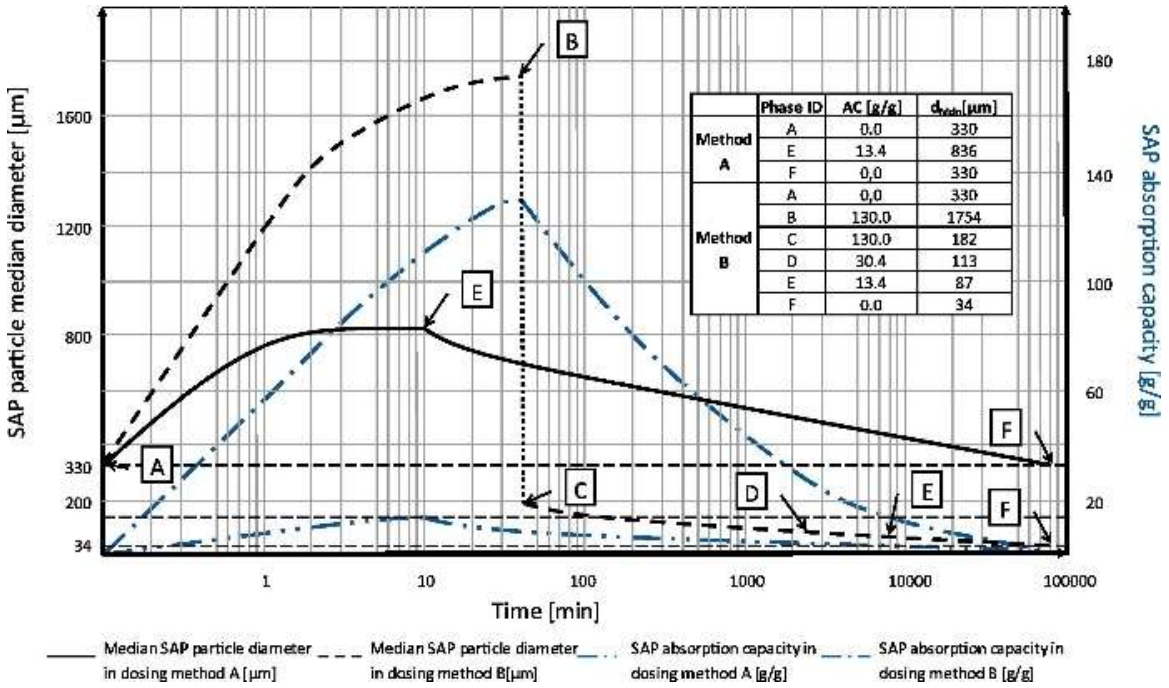
As presented, this process can reduce the median particle size from approximately 330 μm to about 34 μm and increase the specific surface area of the internal curing agent by almost one order of magnitude [7]. Such mechanically induced fragmentation is beneficial for internal curing, as a larger number of smaller SAP fragments are distributed more uniformly within the cement matrix, increasing the contact area between SAP and the surrounding cement. As a result, water desorption from SAP may occur more effectively, improving the homogeneity of internal curing and limiting the risk of localized SAP agglomerates or large SAP-induced voids.

3. RHEOLOGY OF HYDROGELS AND INTERNALLY-CURED CEMENT COMPOSITES

The incorporation of SAP into cementitious composites affects not only the internal moisture balance and hardened microstructure but also the rheological behavior of the fresh mix. This effect is particularly important in self-compacting systems, where the material must exhibit sufficient flowability while maintaining adequate cohesion to prevent bleeding, aggregate particle sedimentation, and segregation of fine functional additions. The rheology of such composites is usually governed by the balance between yield stress, which controls the mixture's ability to initiate flow, and plastic viscosity, which determines the resistance to flow once deformation has started.

The influence of SAP on fresh-state properties depends strongly on the state in which the polymer is introduced into the mixture. When dry, unsaturated SAP is added directly to the mix, the water absorption occurs during mixing and in the early period after mixing [7]. In this case, SAP removes part of the free mixing water from the cement paste environment, thereby reducing the amount of water immediately available for particle lubrication and superplasticizer dispersion. As a result, the effective water-to-binder ratio in the fresh mixture decreases, leading to increased yield stress, reduced flowability, and a higher risk of non-uniform rheological response. Since the absorption capacity of polyacrylic SAP in cement paste is considerably lower than in tap water, dry SAP absorbs water rapidly but only to a limited extent, and this process may be accompanied by particle agglomeration and local formation of SAP-rich zones [20].

A different mechanism occurs when SAP is introduced in a pre-saturated form, as a hydrogel. In this case, the absorption stage is completed before contact with cement and aggregate particles. After the hydrogel is added to the mix, the principal process is no longer absorption of mixing water, but desorption of water from the polymer network into the surrounding cement paste. Thus, in contrast to dry SAP, pre-saturated SAP does not initially compete with cement and mineral additions for free water during mixing. Instead, it



	Phase ID	AC [g/g]	d_{50n} [μm]
Method A	A	0.0	330
	E	13.4	836
	F	0,0	330
Method B	A	0,0	330
	B	130.0	1754
	C	130.0	182
	D	30.4	113
	E	13.4	87
	F	0.0	34

Figure 4. SAP particle median diameter and SAP absorption capacity in time, dependent on the parameters of the environment and the dosing method. Dosing method A – saturation of SAP with mixing water during mixing stage (addition of 'dry' SAP), dosing method B – saturation of SAP with mixing tap water prior to mixing stage (addition of pre-saturated SAP) [7].

behaves as a dispersed, water-containing, deformable phase, gradually releasing water due to differences in electrochemical activity, capillary pressure, and internal stresses developing in the cementitious environment. In hydrogel-modified systems, water transport is reversed immediately upon incorporation into the mix: water is released from the SAP until the polymer reaches equilibrium with the cementitious environment, while fine cement particles and capillary forces disturb and prolong this release (Figure 4).

It should be noted that SAP's susceptibility to mechanically induced changes in water absorption and retention capacity is strongly dependent on its chemical composition and crosslinking structure. Under mechanical stress, the swollen polymer network may undergo partial rupture or fragmentation, disrupting the equilibrium between the osmotic pressure within the hydrogel and the external pressure exerted by the surrounding cementitious medium. This structural disruption may accelerate the release of water previously stored within the SAP network, leading to rapid desorption during mixing or early hardening (Fig. 5).

To assess the susceptibility of SAP hydrogel to rapid water desorption induced by mechanical fragmentation, standard thixotropy tests may be applied. In such a rheological procedure, the hydrogel is subjected to a controlled shear-rate program, in which the shear rate is rapidly increased for a defined period, and the resulting changes in dynamic viscosity are recorded. A pronounced decrease in dynamic viscosity after the high-shear stage, relative to the initial value, indicates disruption of the swollen polymer network. Such degradation reduces SAP's ability to retain water within its structure, increasing the amount of free, unbound water in the system. Therefore, a significant viscosity loss after shear loading can be interpreted as indirect evidence of SAP structural damage and mechanically induced water desorption (Figure 6, Table 1).

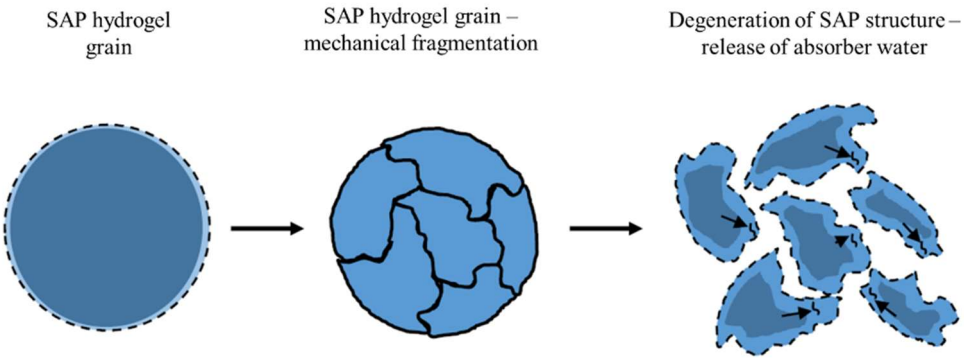


Figure 5. Mechanically-induced water desorption from SAP hydrogel under shear: schematic of partial rupture and fragmentation of the swollen polymer network under mechanical stress during mixing, leading to rapid release of previously retained water.

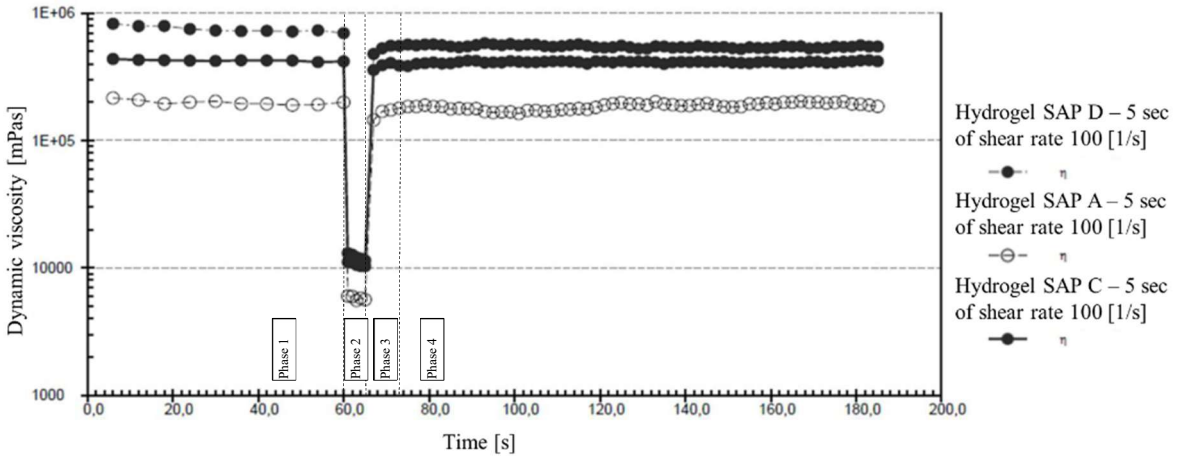


Figure 6. Dynamic viscosity profiles of SAP hydrogels A, C, and D recorded during a four-phase thixotropy test: Phase 1 – initial viscosity at low shear rate (1/s); Phase 2 – viscosity under high shear rate (100 1/s); Phases 3 and 4 – viscosity recovery at 1 1/s within 10 s and after 10 s, respectively. The degree of irreversible viscosity loss between Phase 1 and Phase 4 indicates mechanically-induced structural degradation of the polymer network.

Table 1. Dynamic viscosity of three different SAP hydrogels recorded during a four-phase thixotropy test. Negative differences in the final rows indicate irreversible viscosity loss following high-shear loading, interpreted as evidence of mechanically-induced structural degradation of the polymer network.

	Property	SAP A	SAP C	SAP D
Phase 1	Averaged initial dynamic viscosity for shear rate of 1 [1/s] [Pas]	198.82	424.15	748.08
	SD [Pas]	7.75	6.15	39.19
	CV [%]	3.90	1.45	5.24
Phase 2	Averaged dynamic viscosity for shear rate of 100 [1/s] [Pas]	5.79	10.66	12.20
	SD [Pas]	0.18	0.34	0.58
	CV [%]	3.06	3.18	4.77
Phase 3	Averaged dynamic viscosity up to 10 sec. after reducing shear rate from 100 to 1 [1/s] [Pas]	177.17	394.58	548.12
	SD [Pas]	12.27	14.91	25.94
	CV [%]	6.93	3.78	4.73
Phase 4	Averaged dynamic viscosity after 10 sec. after reducing shear rate from 100 to 1 [1/s] [Pas]	186.34	413.70	546.24
	SD [Pas]	11.18	5.72	13.10
	CV [%]	6.00	1.38	2.40
Change in average dynamic viscosity (Phase 3 – Phase 1)		**-10.89**	**-6.97**	**-26.73**
Change in average dynamic viscosity (Phase 4 – Phase 1)		**-6.27**	**-2.46**	**-26.98**

In self-compacting cementitious composites, the most desirable rheological modification is not necessarily a general increase in flow resistance, but rather a selective increase in plastic viscosity while maintaining a relatively low yield stress. A low yield stress enables the mixture to initiate flow under its own weight, whereas sufficient plastic viscosity limits bleeding, aggregate settlement, and segregation of fine functional constituents. SAP in the form of a hydrogel is particularly suitable for this purpose as it does not rapidly absorb free mixing water, and therefore does not significantly disturb the initial water availability responsible for flow initiation. At the same time, the swollen hydrogel particles act as deformable inclusions dispersed in the cement paste, reducing internal friction and increasing energy dissipation during flow.

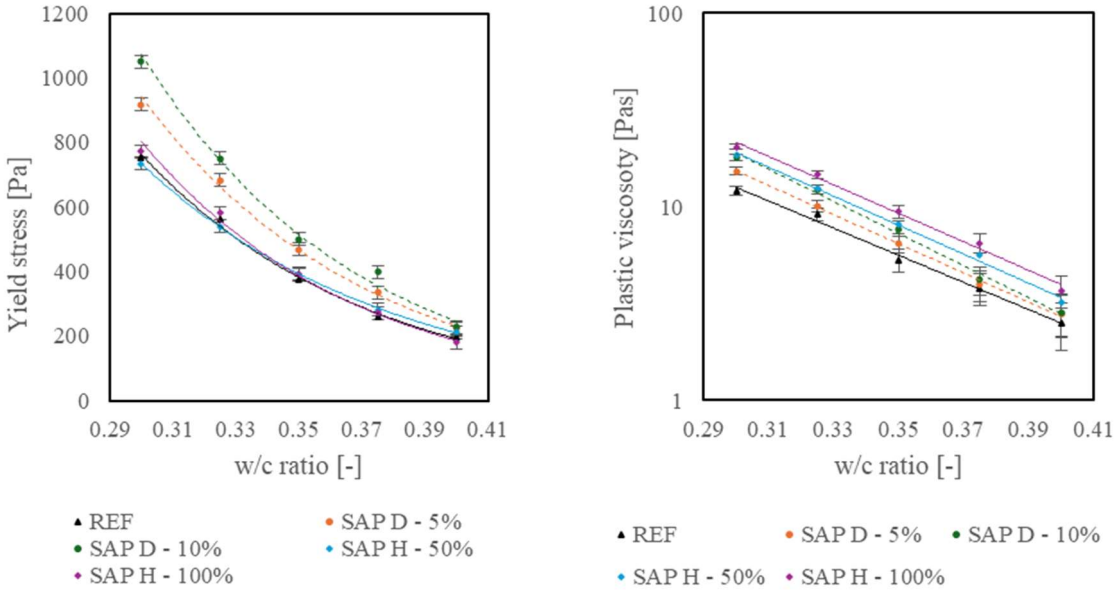


Figure 7. Rheological characterization of SAP-modified cement pastes: (a) flow curves illustrating the effect of SAP hydrogel content on yield stress relative to the reference mix; (b) flow curves illustrating the effect of SAP hydrogel content on plastic viscosity relative to the reference mixture. SAP D – SAP added in a dry state; SAP H – SAP added in the hydrogel state; 5-100% - amount of mixing water initially absorbed by SAP.

Consequently, properly designed SAP hydrogel addition may improve mix stability by increasing plastic viscosity, while the yield stress can remain at a level compatible with self-compacting behavior through appropriate adjustment of the superplasticizer dosage and effective water-to-binder ratio (Figure 7).

The stabilizing effect of SAP hydrogel is especially relevant in high-performance composites containing high amounts of fine particles or functional modifiers, such as photocatalytic TiO_2. In such systems, segregation resistance and uniform distribution of constituents are decisive for their final performance. A hydrogel-modified matrix reduces sedimentation of heavier particles, limits bleeding, and improves the homogeneity of the functional phase distribution. This effect results from the combined action of increased plastic viscosity, gradual water release, and mechanical fragmentation of hydrogel particles during mixing. Fragmentation produces smaller SAP fragments with a higher specific surface area and a more uniform distribution within the matrix, thereby further improving the interaction between SAP and the cement paste.

However, the rheological properties of the SAP hydrogel must be carefully controlled. Excessive SAP content or excessive entrained water may increase the total water-to-cement ratio and negatively affect the hardened properties of the composite [10]. For this reason, the design of SAP-modified cement composites should distinguish between effective water, which governs the rheology of the cement paste, and water entrained in SAP, which primarily acts as internal curing water. The relationship between total, effective, and entrained water-to-cement ratios is therefore essential for interpreting both fresh and hardened properties of internally cured composites [7,10,20]. Consequently, the use of SAP hydrogel in self-compacting cementitious composites should be designed as a coupled rheological and curing modification. This is particularly important for thin,

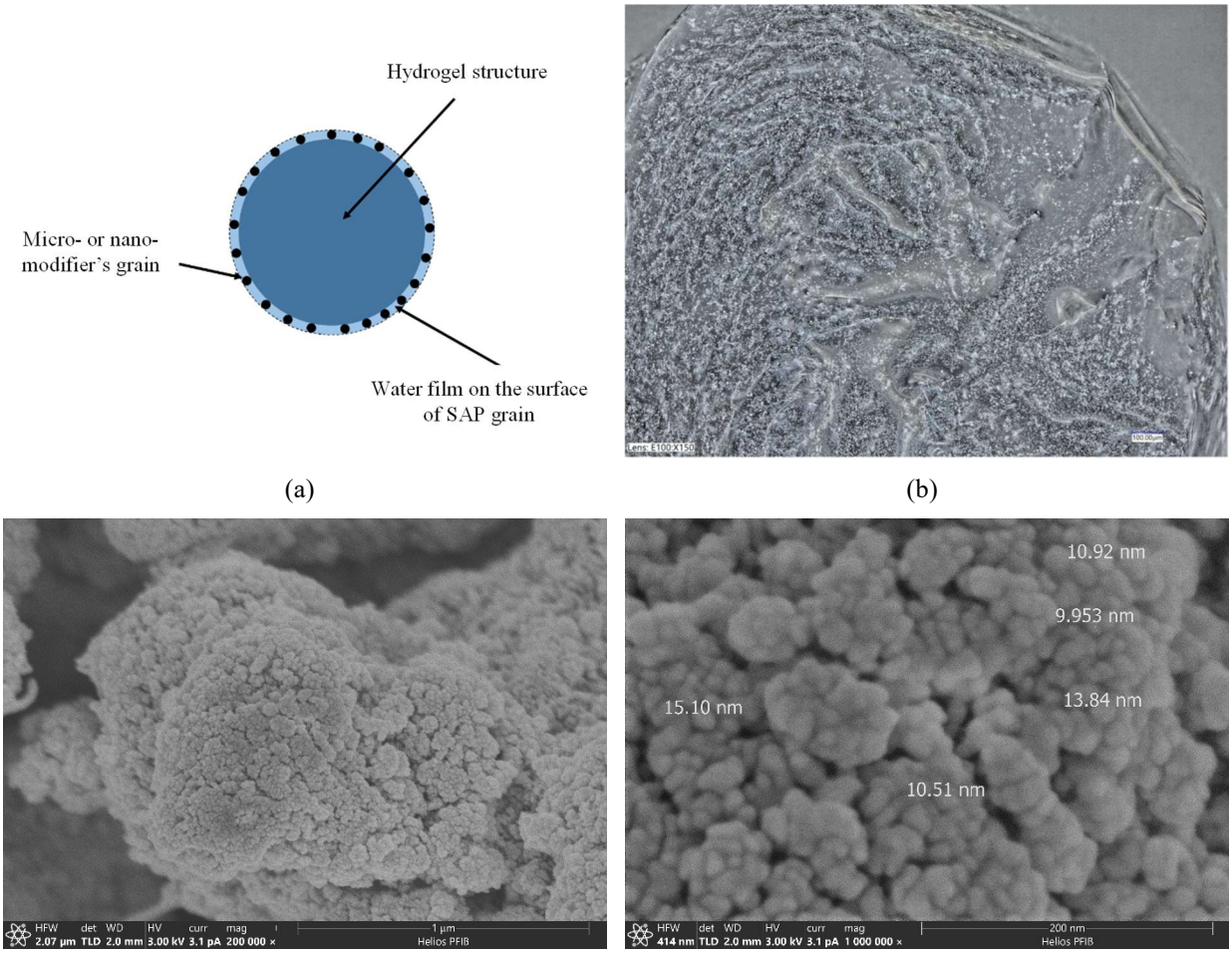


Figure 8. SEM images of SAP hydrogel particles loaded with TiO_2: (a) schematic showing uniform coverage of photocatalytic TiO_2 grains on the external surface of swollen SAP hydrogel particles; (b) optic microscopy image of hydrogel grain uniformly covered with TiO_2 grains [21]; (c, d) detail views showing the homogeneous distribution and adhesion of TiO_2 particles within the water film surrounding the hydrogel grain, supporting the role of SAP as a temporary carrier and dispersing medium for the photocatalytic modifier.

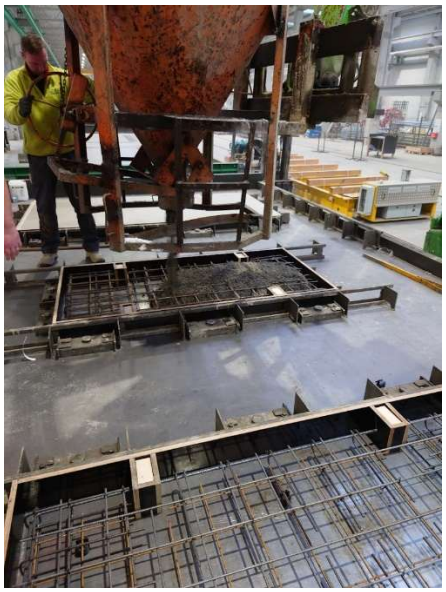
functional, self-leveling, high-performance layers applied to prefabricated concrete elements, where the composite must spread uniformly over the substrate and ensure a homogeneous distribution of photocatalytic or other functional particles in the near-surface zone. In this sense, SAP hydrogel may serve not only as an internal curing agent, but also as a rheology-controlling component enabling the production of stable, self-compacting, functionally tailored cementitious surfaces.

4. HYDROGEL APPLICATION IN HIGH-PERFORMANCE SELF-LEVELING PHOTOCATALYTIC CEMENT COMPOSITES

An additional function of SAP hydrogel particles, beyond internal curing and rheological modification, is their potential use as carriers for micro- and nano-sized functional fillers. This function is particularly relevant in self-compacting cementitious composites, where the uniform distribution of fine modifiers is often difficult to achieve due to their high specific surface area, strong tendency to agglomerate, and susceptibility to segregation during flow. In the case of SAP introduced as a hydrogel, a thin water film present on the external surface of swollen polymer particles serves as an intermediate zone for the temporary attachment or adsorption of fine particles [21]. As a result, functional modifiers such as TiO_2, graphene oxide, nano-SiO_2, or other photocatalytic and micro- and nano-additives may be distributed on the surface of SAP grains before incorporation into the cementitious matrix. This mechanism reduces agglomeration and improves the spatial distribution of the modifier in the cement matrix, especially when the mix is designed as a highly flowable, self-compacting one. Microscopic observations of SAP hydrogel particles coated with TiO_2 showed a uniform distribution of photocatalyst



(a)



(b)



(c)

Figure 9. Two-layer prefabricated element concept with SAP–TiO_2 photocatalytic surface layer: (a) thin fine-grained self-compacting photocatalytic cementitious composite placed in the mold, (b) placement of structural layer (non-photocatalytic), (c) the near-surface zone of the demolded element showing the finished functional layer.

grains on the hydrogel surface, supporting the concept of SAP hydrogel as a temporary carrier and dispersing medium for functional particles (Figure 8).

The use of SAP hydrogel as a carrier of photocatalytic particles is particularly justified in the design of thin functional surface layers. Photocatalytic reactions occur mainly in the near-surface zone, where the photocatalyst has access to electromagnetic radiation, oxygen, water vapor, and gaseous pollutants [22-24]. Therefore, the distribution of TiO_2 throughout the full volume of a concrete element is technologically inefficient and economically unfavorable. A more rational approach is to concentrate the photocatalyst only in a thin cementitious layer applied to the surface of a prefabricated element. In such a system, the base concrete provides mechanical performance, dimensional stability, and load-bearing capacity, whereas the fine-grained self-leveling photocatalytic layer provides the required surface functionality. This two-layer concept reduces consumption of photocatalytic material while maintaining the active surface area required for pollutant degradation. The practical realization of this requires a preparation method that ensures uniform distribution of TiO_2 within the thin functional layer while avoiding particle agglomeration, which would reduce the accessible photocatalytic surface area and compromise both air-purification efficiency and microstructural homogeneity. SAP hydrogel meets this requirement by serving as both a dispersing medium for the photocatalyst during the composite's preparation.

The preparation of a SAP-based photocatalytic dispersion should be designed to ensure both stable suspension of TiO_2 particles and controlled interaction between the photocatalyst and the hydrogel surface. In the proposed procedure, TiO_2 powder is dispersed in mechanically fragmented hydrogel using high-shear mixing in a mechanical dissolver to break down loose agglomerates and obtain a homogeneous suspension. During this stage, part of the modifier becomes located in the water film surrounding the swollen SAP grains and on their external surface. The resulting SAP–TiO_2 hydrogel dispersion may then be incorporated into the cementitious composite (Figure 8c and 8d).

A fine-grained self-compacting cementitious composite intended for such an application should be designed with a low effective water-to-binder ratio, a suitable superplasticizer dosage, and controlled SAP hydrogel content. The absence of coarse aggregate in the functional layer facilitates the formation of a smooth surface and allows the layer to be applied in small thicknesses. At the same time, the rheological properties must be adjusted to allow self-leveling, taking into account the properties of the used SAP, especially the mechanically induced fragmentation and changes in water desorption kinetics (Figure 9).

The proposed technological sequence for manufacturing a two-layer prefabricated element includes: preparation of the SAP–TiO_2 hydrogel dispersion; preparation of a fine-grained self-compacting mortar; application of the functional mortar layer onto the mold or onto the surface of the base concrete; casting or joining with the structural concrete layer; and curing under conditions allowing proper hydration. In this arrangement, SAP performs several functions simultaneously. First, it provides internal curing water to the thin cementitious layer. Second, it modifies the rheology of the fresh mortar and improves stability during flow. Third, it acts as a carrier for the photocatalyst, supporting its distribution in the near-surface region. Finally, after water desorption, SAP-related voids modify the near-surface porosity, increasing the accessible surface area and improving contact between pollutants and active TiO_2 particles.

To prove the concept, the photocatalytic air-purification performance of cementitious composites modified with SAP–TiO_2 hydrogel dispersions was evaluated using a procedure based on ISO 22197-1:2016 [25]. However, the test conditions were deliberately modified to better represent less favorable environmental exposure typical of autumn–winter conditions in Poland. Compared with the standard procedure, the UV-A irradiance was reduced tenfold, from 10 W/m² to 1 W/m², and the initial nitrogen oxide concentration was reduced from 1000 ppb to 100 ppb. The latter modification was introduced to reproduce pollutant concentrations closer to those recorded at traffic-related air-quality monitoring stations in Polish urban agglomerations.

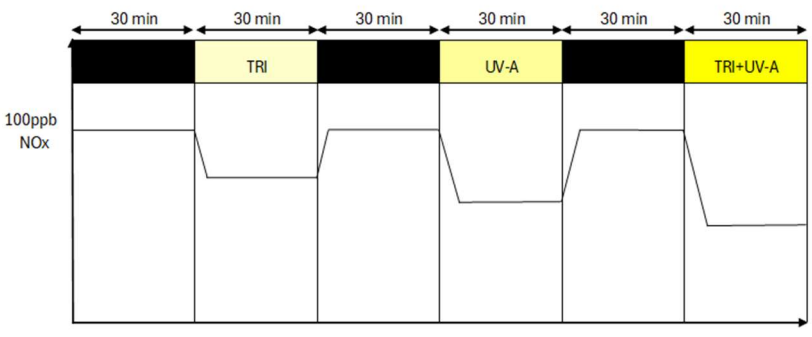


Figure 10. Schematic of the test procedure for photocatalytic efficiency in the removal of nitrogen oxides under different irradiation conditions.

The tests were performed under three irradiation regimes: UV-A radiation at 1 W/m², visible light without the UV range at 150 W/m², and combined irradiation consisting of visible light at 150 W/m² and UV-A radiation at 1 W/m² (Figure 10). The specimens (140 x 160 x 40 mm), made from the same high-performance composite used for the visualized large-scale elements, were tested after 28 days of curing in a climatic chamber. Before testing, the photoactive surfaces were cleaned with distilled water and dried. The results were expressed as mean values of air-purification efficiency, ΔNO, defined as the difference between the mass of removed NO and the mass of generated NO_2, expressed in μg/(h·m²) of photocatalytic surface.

The photocatalytic efficiency of cementitious composites is governed not only by the amount of TiO_2 incorporated into the material, but also by the accessibility of the active phase to the external environment [26,27]. This accessibility is controlled, among other factors, by the morphology and connectivity of the near-surface pore network [28]. In this context, hydrogel modification influences photocatalytic performance indirectly by altering the pore structure. In the presented results (Figure 11), the mass content of the photocatalytic modifier in the cement composite was kept at the same level between all analyzed series – assumed independent variables only changed the composition of dispersion itself - TiO_2 content (7.5% or 17.5% mass of dispersion) and SAP concentration (69% or 100% of water in dispersions absorbed by added SAP).

Beyond its role as an internal curing agent, SAP acts as a pore-structure modifier in the hardened cement matrix. Upon completion of water desorption, the emptied and partially collapsed polymer network leaves behind discrete voids – commonly referred to as "SAP-induced pores" or "quasi-pores" – whose geometry and spatial distribution reflect the size and dispersion state of the original SAP particles [7]. Although these voids increase the total porosity of the cement matrix, their discontinuous character interrupts the connectivity of the capillary pore network, thereby reducing the effective transport coefficient for aggressive species. This microstructural modification has been documented to improve freeze–thaw resistance, reduce chloride diffusivity, and limit the ingress of sulfate and carbonation fronts, collectively contributing to the long-term durability of the composite [29].

For this reason, the presented air-purification results can be explained by the pore-network modifications identified by mercury intrusion porosimetry (Figure 12), which showed that composites modified with SAP–TiO_2 hydrogel dispersions exhibited a higher capillary pore content relative to the reference series in which TiO_2 was introduced solely as an aqueous dispersion, irrespective of the TiO_2 concentration or SAP saturation level. This increase in capillary porosity was attributed to the combined effect of SAP-induced quasi-pore formation and the partial redistribution of the cement paste microstructure in the vicinity of hydrogel particle remnants. The resulting network of finer, better-connected pores in the near-surface zone improved the accessibility of gaseous nitrogen oxide species to the photocatalytically active TiO_2 particles, thereby increasing the effective reactive surface area and enhancing pollutant degradation efficiency. Importantly, the capillary porosity of SAP-modified photocatalytic mortars remained consistently lower than that of the reference mortar of the same base composition without either TiO_2 or SAP, confirming

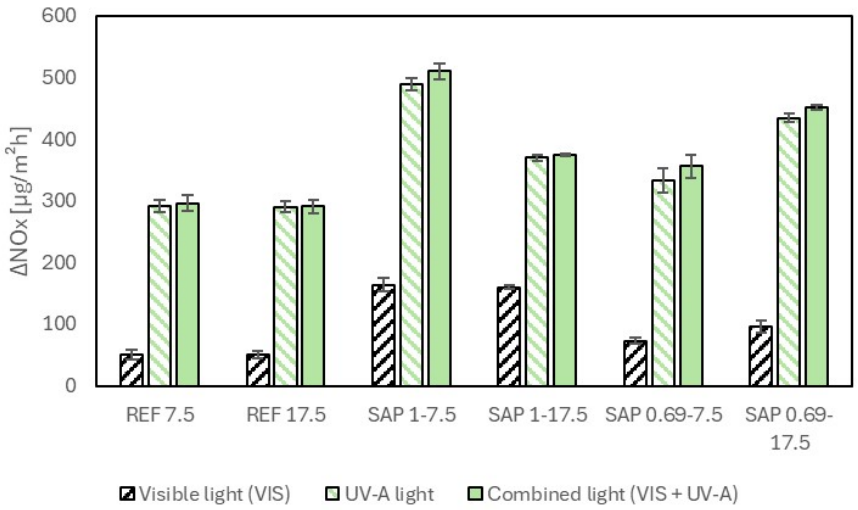


Figure 11. Air-purification efficiency of SAP–TiO_2-modified cementitious composites expressed as mean ΔNO [μg/m²h] under three irradiation regimes: UV-A radiation at 1 W/m², visible light at 150 W/m², and combined UV-A plus visible light irradiation. Results are shown for series differing in TiO_2 content (7.5% and 17.5% by mass of dispersion) and SAP saturation level (69% and 100% of dispersion water absorbed by SAP), compared with a reference series in which TiO_2 was introduced as an aqueous dispersion without SAP.

that the pore-structure modifications introduced by SAP hydrogel did not lead to uncontrolled pore coarsening or a deterioration of the overall microstructural quality. The proposed approach thus demonstrates the potential of SAP–TiO_2 hydrogel dispersions as a technologically viable strategy for producing durable, photocatalytically active self-compacting cementitious coatings for prefabricated elements intended for deployment in urban environments with elevated traffic-related air pollution.

5. SUMMARY

Superabsorbent polymers constitute a versatile group of internal curing agents whose water-absorption, retention, and release characteristics can be adjusted through polymer chemistry, particle size, crosslinking density, and method of incorporation into the cementitious mix. Hydrogel-modified mixes, if designed properly, can exhibit a selective increase in plastic viscosity without a proportional increase in yield stress, which is especially beneficial when high flowability must be combined with resistance to segregation. Moreover, the mechanism of mechanically-induced fragmentation of swollen SAP particles during mixing can be used to design a finer, more uniformly distributed internal curing phase within the cement matrix, increasing the contact area between SAP and the surrounding cement paste and improving the homogeneity of water desorption during hydration, and, after hardening, contributing to intentional changes to pore network characteristics of the composite.

The concept of leveraging those phenomena to develop high-performance composites was demonstrated by incorporating SAP hydrogel as a carrier for photocatalytic TiO_2 particles, as confirmed at both microscopic and material-performance levels. Microscopic observations demonstrated the uniform attachment of TiO_2 particles to the hydrogel surface, while air-purification tests performed under reduced UV-A irradiance and pollutant concentrations representative of urban exposure conditions showed improved NO removal efficiency in SAP–TiO_2-modified composites compared with the reference series. Mercury intrusion porosimetry indicated that this improvement results from the combined effect of enhanced photocatalyst dispersion and a more favorable near-surface pore structure, which facilitated the transport of gaseous pollutants to the active TiO_2 phase without causing uncontrolled pore coarsening. A patent application for the aforementioned technology (Method for producing hydrogel photocatalytic dispersions with increased stability, hydrogel photocatalytic dispersion with increased stability, use of hydrogel photocatalytic dispersion and photocatalytic cement composite) was filed with the Patent Office of the Republic of Poland under the number P.453434.

The presented data show that the SAP hydrogel may act simultaneously as an internal curing agent, a rheology-controlling component, and a carrier for functional fillers. This multifunctionality is particularly valuable in the design of thin, high-performance, self-compacting photocatalytic surface layers applied to prefabricated concrete elements, where material efficiency, surface functionality, and production feasibility must be optimized together.

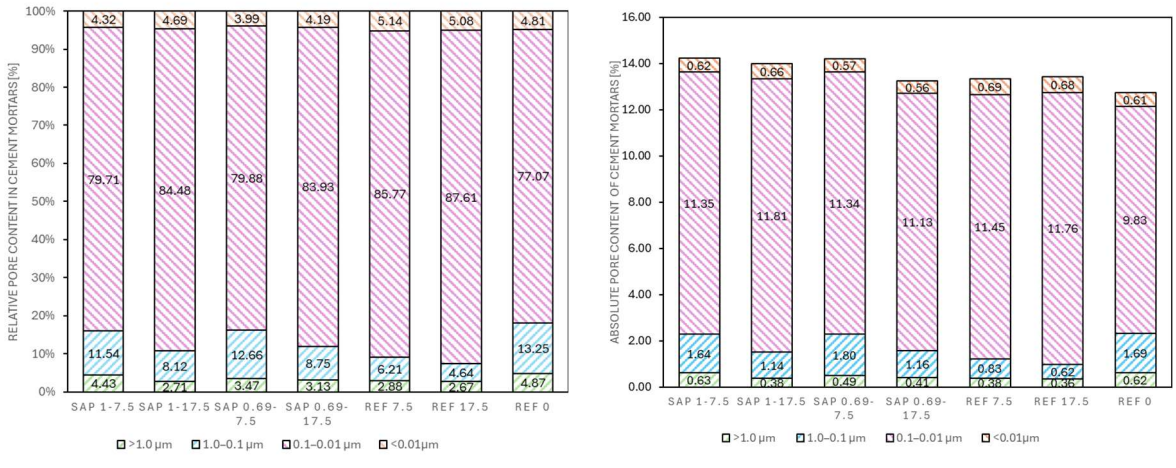


Figure 12. Mercury intrusion porosimetry (MIP) results for SAP–TiO_2-modified cementitious composites after 28 days of curing in climatic chamber (RH = 95%, temperature = 20ºC): (a) relative pore size distribution for reference and SAP-modified series, illustrating the shift in capillary pore content as a function of TiO_2 concentration and SAP saturation level; (b) absolute pore size distribution for reference and SAP-modified series.

ACKNOWLEDGMENTS

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33. SLOVENSKI KOLOKVIJ O BETONIH

Possibilities for Application of Different Materials in Self-Compacting Concrete

Možnosti uporabe različnih materialov v samozgoščevalnem betonu

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Abstract

Self-Compacting Concrete (SCC) is considered as one of the greatest innovations of the 20th century's last decades. With raising awareness of the importance for preserving the natural resources and environment as a whole, the possibilities for application of different materials, including waste and recycled materials in the production of the SCC, were analyzed. Results of more than 20 different SCC mixtures were presented in the paper, including their composition and records on their flowability, viscosity and passing ability, together with compressive strength and water permeability at the age of 28 days. Obtained results are very encouraging from the environmental aspect, especially regarding the application of fly ash and recycled concrete aggregates in the SCC.

Povzetek

Samozgoščevalni beton (SCC) velja za eno največjih inovacij zadnjih desetletij 20. stoletja. Glede na vse večjo ozaveščenost o pomenu ohranjanja naravnih virov in okolja kot celote so bile analizirane možnosti uporabe različnih materialov, vključno z odpadki in recikliranimi materiali, pri proizvodnji SCC. V članku so bili predstavljeni rezultati več kot 20 različnih mešanic SCC, vključno z njihovo sestavo in podatki o njihovi pretočnosti, viskoznosti in sposobnosti prehoda, skupaj s tlačno trdnostjo in prepustnostjo za vodo po 28 dneh. Doseženi rezultati so z okoljskega vidika zelo spodbudni, zlasti kar zadeva uporabo pepela in recikliranih betonskih agregatov v samozgoščevalnem betonu.

Keywords: self-compacting concrete, fly ash, recycled concrete aggregate, flowability, viscosity, compressive strength, watertightness

Ključne besede: samozgoščevalni beton, elektrofiltrski pepel, reciklirani betonski agregat, pretočnost, viskoznost, tlačna trdnost, neprepustnost za vodo

1. INTRODUCTION

Not as famous as the industrial revolution in the mid XIX century that enabled widespread use of reinforced concrete at the world scale, the revolution in the concrete production happened in the last two decades of the XX century. This extraordinary fast and uncompromising development of concrete for structural needs that occurred not more than 40 years ago was evoked by the development of chemical industry, and therefore new and powerful chemical admixtures: in the first-place carboxylate-based High-Range Water Reducing Admixtures (HRWRA). When the possibility was recognized, it didn't take long to define the needed properties of the new concrete material known now as Self-Compacting Concrete (SCC). Subsequent research converged fast to this special concrete known for its properties: specific composition, superior flow and filling capability, passing ability, segregation resistance, and high strengths. These properties are the key drivers enabling the advantages that SCC is famous for: no vibration required for its placement, faster concrete works, flowing even through the densest reinforcement cages, filling the most complicated formwork geometries, decrease of skilled workers number at the construction site, faster formwork removal, reduced noise pollution, and exceptional surface finishing.

Emerged in the highly standardized world that recognized quality more than the world we live in now, the development of SCC was followed by the knowledge gathering of the most advanced concrete research centers, which paved a way to specific institution-based recommendations. These recommendations were further developed into Specifications and guidelines published mid-2000's [1], and further tailored into standards as we know them at the present time, for instance European Norms (EN 12350:8-12) covering this field, which date back to the 2010.

Comparatively to the development of SCC worldwide, Serbian experience, fueled by the findings from the available sources in the 1990's, resulted with the development of the first successful SCC mixtures at the first years of the 2000's and with several master's theses defended at the University of Belgrade Faculty of Civil Engineering as early as of 2003. and 2004. [2-4]. After that, development of the SCC took place also in other Serbian university centers, and industrial research facilities. Nowadays, there are just a few concrete production plants in Serbia that do not offer SCC in their portfolio as an option for most demanding applications.

Consciousness related to the worldwide ever rising energy consumption, and depraved impact on the environment, provoked measures in the sphere of sustainability and environmental preservation, which were well implemented in the production of SCC. This extraordinary concrete type is now a fertile ground for use of different component materials, not stopping at the research level, but also providing industrial scope of sustainable construction [5,6].

This paper presents some of the results obtained in more than two decades period, as part of laboratory research projects conducted at the Laboratory for materials of the Institute of Materials and Structures, University of Belgrade Faculty of Civil Engineering. These results confirm the basic principles of the concrete technology, regarding laws that connect structure of the fresh and hardened concrete to the mechanisms taking place in the life of this complex and highly rewarding building material.

2. MATERIALS USED IN THE PRODUCTION OF SCC

The basic component materials used in the production of the SCC are fine and coarse aggregates, cement, mineral and chemical admixtures, and water.

It is considered that for the preparation of SCC, concrete aggregates with continuous grain size distribution, give better results, regarding the flowability of the fresh concrete [7]. The fresh state properties of SCC are in close relation with the amount and sizes of different aggregate grains. The good packaging of the grains would lead to smaller need for chemical admixtures, as well as to lower segregation potential. For the interaction between aggregate grains, apart from their size, the shape is also very important. When crushed aggregates are used for SCC production, it was concluded that higher amount of cement paste, and smaller amount of aggregate should be used in order to avoid inter-locking effect [8].

Based on the results found in literature all types of cement (CEM I, CEM II, CEM IV, sulfate resistant cement) have been successfully used in production of SCC. The type of cement used was usually dictated by environmental conditions and market availability, rather than specific demands related to SCC production.

Usually, for the production of SCC, high amounts of fine particles are necessary. Since, it would be very expensive to use only cement for this purpose, different mineral fillers are usually applied. The effects of these materials on the properties of fresh concrete need to be thoroughly investigated before application. Mineral additons are classified into two groups based on their ability to react with other concrete components and form structures that would influence the mechanical properties of concrete: inert or almost inert additions (Type I) and pozzolanic or latent hydraulic additions (Type II) [9,10].

2.1. Limestone filler (LF)

Limestone filler is most common mineral addition used in the production of SCC. It belongs to Type I of additions, with the foundation that it does not influence the hydration of cement. Nevertheless, it is found that very fine particles of limestone can form nucleation point for the hydration of cement, and increasing the strength development in the early ages of concrete. Addition of limestone filler increases critical limit of shear stresses, but does not show visible effects on the plastic viscosity and slump flow test results [11].

2.2. Fly ash (FA)

Fly ash is a waste material obtained after burning of the solid fuels such as coal. It has the ability to react with calcium hydroxide at the room temperature, due to presence of SiO_2 and Al_2O_3 in amorphous state in its composition. With increase of fineness of fly ash up to the 6000 cm2/g it is possible to increase its pozzolanic activity. Standard EN 450 [12] defines the application of fly ash in concrete mixtures, regarding its classification, selection, sieving, drying mixing, milling and carbon dioxide reduction. There are several conditions that have to be met in order to apply fly ash as mineral additions to concrete. These conditions are related to its chemical composition, fineness, bulk density, stability and activity index, and also to its influence on the setting time. Standard EN 206-1 [13] defines effects of fly ash application in concrete mix design through implementation of k value in the calculation of water-to-cement factor.

As far as its influence on the concrete fresh state properties is concerned, the spherical particles of fly ash, with appropriate fineness, increase the concrete moveability, which can further lead to the reduction of water necessary for the concrete mix [14]. It is also

considered that concrete pumpability increases with addition of fly ash. All of these findings should lead to its possible application as mineral addition in SCC [15,16]. Nevertheless, it is reported that the addition of fly ash to SCC mix, leads to shorter workability period and reduces its passing ability period [17]. The addition of fly ash also increases the segregation resistance as well as concrete bleeding. All types of fly ash that are classified as F have influence on the hydration process of cement through increase of the setting time.

2.3. Recycled concrete aggregate (RCA)

RCA properties can be diverse, due to different factors, such as its origin, the dosage and components of original concrete, as well as the crushing process of the original elements. Revilla-Cuesta et al. [18] performed overview of the RCA properties, such as saturated-surface dry density and water absorption of fine and coarse RCA, based on the results found in literature. The SSD ranged between 2.38 and 2.48 g/cm^3 for coarse RCA, and 2.21 to 2.39 g/cm^3 for fine RCA. Water absorption was higher for fine aggregates, ranging between 7.76 and 11.06%, when compared to coarse aggregates with water absorption ranging between 4.53 and 6.27%. Since the SCC usually has high cement content and low volume of coarse aggregates, it has been found by several authors that the application of RCA in SCC can be more successful than in the case of incorporation of RCA in ordinary concrete [19].

Revilla-Cuesta et al. also concluded that the increase in percentage of RCA substitution increases the viscosity of the mixtures and reduces their flowability. It was noticed that although more water is necessary for concrete containing RCA due to its water absorption, the additional water is sometimes insufficient to compensate for the water absorbed by the aggregates [18].

Kou et al. [20] investigated influence of total replacement of coarse aggregates with recycled concrete aggregate, with different levels of replacement of fine aggregate on the properties of SCC. As filler, the authors used fly ash in all of the concrete mixtures. Increased level of fine recycled concrete aggregate led to increase in slump flow diameter and to increase in blocking effect.

Ground recycled concrete can be used as partial replacement of filler. Sun et al. [21] investigated the influence of the all three types of the recycled concrete on the fresh state and hardened properties of SCC mixtures. The authors concluded that the flowability of the SCC can meet the quality standards, if the amount of the partial replacement of aggregates and filler is limited. They recommend that the level of replacement should not exceed 10% for filler if coarse RCA is up to 100% used as coarse aggregates, or 20% when coarse RCA is up to 50% used as coarse aggregates.

The influence of RCA addition on the compressive strength of the SCC cannot be strictly established, as high dispersion of the results is found in literature. It was shown that the uncertainty increases with the increase of the RCA replacement rate [18].

2.4. Ceramic waste aggregate (CWA)

Waste ceramic aggregates that are accumulated origin mainly from the unconformed production of ceramics and from the construction and demolition origin. It was shown that the addition of waste ceramic aggregate led to increased dosage of superplasticizer than for the reference mixture. Based on the fresh, hardened properties and durability, Meena et al. concluded that it is possible to produce SCC with 100% of waste ceramic aggregates [22].

2.5. Crumbed rubber aggregate (CR)

Crumbed rubber aggregate obtained through crushing and milling of the tires has been successfully implemented as concrete and mortar component [23-26]. It was noticed that increase in the recycled rubber aggregate content and decrease in the size of the rubber aggregate leads to the reduction of workability of the concrete in question, and to the reduction of the mechanical strength of concrete. The reductions in workability are explained through high inter-particle friction, high surface roughness and low density of this type of aggregate, while the reduction in mechanical properties are explained through significant differences in modulus of elasticity between rubber aggregate and other concrete phases, weak interface between the rubber aggregate grains and cement stone, and the defects generated during the casting process [27]. When recycled rubber aggregates are used together with RCA as partial replacement of natural aggregates (NA), it was concluded that the mechanical properties decrease dramatically, while water absorption and porosity increase. Still, it was possible to produce the SCC with compressive strength greater than 31 MPa, using 30% of recycled rubber aggregate with maximum grain size of 4.75 mm and 100% of coarse RCA [28].

2.6. Fibers (FI)

The addition of fibers leads to increase in flexural and tensile strength of concrete, as well as the increase in its durability. As it is expected, fiber type, material properties, shape, volume and distribution will influence the properties of fresh and hardened SCC. Zeyad [29] investigated the effect of fiber types on the fresh properties and flexural toughness of SCC, using hook-end steel fibers, polypropylene fibers, fibers obtained from the waste as mild steel, curved steel, and basalt rock fibers. It was concluded that addition of polypropylene and hooked-end steel fibers had the most pronounced influence on the reduction of workability of SCC mixtures. It was also found that the addition of polypropylene and basalt rock fibers reduced segregation of SCC, while other types of fibers increased segregation.

Table 1. Composition of the tested mixtures with recycled concrete aggregates (kg/m^3) [36]

Mixture		REF	CII100	CIII100	C100
Cement		380			
Limestone powder		250			
Aggregate (0/4 mm)	NA	860			
Aggregate (4/8 mm)	NA	530	0	530	0
	RCA	0	530	0	530
Aggregate (8/16 mm)	NA	310	310	0	0
	RCA	0	0	310	310
Water		194	202	205	205
Superplasticizer		5.7			

Table 2. Properties in fresh and hardened state of the test mixtures containing RCA [36]

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength on 15 cm cube (MPa)	Water penetration depth (mm)
REF	890	2.0	7.4	1	50.5	34
CII100	865	2.1	11.2	0.97	48.5	30
CIII100	840	2.3	7.5	0.94	51.2	29
C100	870	2.5	12.4	0.94	51.1	26

3. EXPERIMENTAL RESEARCH

The experimental research presented in this paper summarizes the tests conducted on SCC with different recycled aggregates, waste materials and mineral additives performed in the Laboratory of Materials at the Faculty of Civil Engineering University of Belgrade. For each of the conducted experiments the mixture design is presented, and then fresh and hardened state properties are discussed. Since the fresh state properties of the SCC cannot be defined using only one of the testing methods, three tests were chosen to describe these properties of different mixtures. Flowability and viscosity were evaluated through the slump flow and t500 slump time measurements [30] and V-funnel test [31]. For the passing ability L-box test was applied [32]. Bulk density was also measured in fresh state [33]. Compressive strength was tested after the age of 28 days on 150 mm cubes [34]. Additionally, bulk density in fresh and hardened state was measured. Also, when possible, depth of water penetration under pressure was measured at the same age [35].

3.1. SCC mixtures with recycled concrete aggregate (RCA)

In the following study, second and third fraction of coarse natural river aggregate were completely replaced by RCA. Portland cement CEM II/A (S-L) 42.5R was used, while the limestone filler had grains smaller than 0.25 mm. Mix design of all tested mixtures is presented in Table 1. Water absorption of the RCA was 3.4% for both fractions of aggregate.

Obtained results are summarized in Table 2. Mixtures containing RCA showed good flowability and higher viscosity than referent mixture. Concrete mix designated as RCIII100 belongs to SF3 class, while all other mixtures reached slump-flow diameter larger than 850 mm. All the mixtures were classified as VS2 according to slump flow time measurements. Reference mixture and RCIII100 mixture were classified as VF1 class, according to V-funnel time, while mixtures RCII100 and RC100 were classified as VF2 class, according to the same criteria. Still, the incorporation of RCA did not provoke blocking effect. Bulk densities of fresh mix varied between 2352 kg/m^3 and 2386 kg/m^3. Also, addition of RCA did not influence the compressive strength at the age of 28 days.

3.2. SCC mixtures with fly ash and recycled concrete aggregate

In the presented research SCC mixtures were prepared using RCA, with maximum grain size of 16 mm. In this case Particle packing density method was used for defining the composition of the concrete mixtures [37].

Bulk density of RCA fractions ranged between 1150 kg/m^3 and 1250 kg/m^3. Water absorption of the fine fraction of RCA was 13.6%, while water absorption for coarse RCA was 1.5% for fraction 4/8 mm and 4% for fraction 8/16 mm. Portland composite cement CEM

Table 3. Composition of the tested mixtures with FA and RCA (kg/m^3) [38]

Mixture		FA100F0C0	FA100F0C100	FA100F50C100	FA100F100C100
Cement		404			
Fly ash		181.2			
Aggregate (0/4 mm)	NA*	695.0	695.0	347.5	0.0
	RCA*	0.0	43.1	347.5	695.0
Aggregate (4/8 mm)	NA	347.5	0.0	0.0	0.0
	RCA	0.0	347.5	347.5	347.5
Aggregate (8/16 mm)	NA	347.5	0.0	0.0	0.0
	RCA	0.0	347.5	347.5	347.5
Water		200.0	206.0	249.0	296.4
Superplasticizer		6.1			

*NA – natural aggregate, RCA – recycled concrete aggregate

Table 4. Properties in fresh and hardened state of the test mixtures with FA and RCA [38]

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength (MPa)	Water penetration depth (mm)
FA100F0C0	910	1.89	18.84	1.00	74.0	10.0
FA100 F0C100	895	1.85	23.32	1.00	70.6	14.8
FA100 F50C100	895	1.90	32.00	1.00	67.3	12.8
FA100F100C100	910	2.45	19.65	0.92	54.3	14.3

II/A-M (S-L) was used in all of the tested mixtures. Fly ash originating from Nikola Tesla B thermal power plant, was used as filler in SCC and its content was around 30% of total binder content. Composition of mixtures is presented in Table 3. Reference mixture was prepared using only natural river aggregate, while in other mixtures aggregates were partially or completely replaced with recycled concrete aggregates (50% or 100% replacement of first fraction (F) and 100% replacement of 2nd and 3rd fraction (C). Obtained results in fresh and hardened state are presented in Table 4.

Bulk density in the fresh state ranged between 2144 kg/m^3 and 2301 kg/m^3. All of the tested mixtures showed high flowability, and were classified as SF3 (Figure 1). Only the mixture containing both fine and coarse recycled concrete aggregate had higher viscosity, measured through slump flow time. Measured V-funnel time for mixture FA100F0C100 was too high, and this mixture could not be classified according to this method. Other three mixtures were classified as VF2 class.



Figure 1. Slump-flow measurements for the mixture FA100F100C100.

Table 5. Composition of the tested mixtures with ceramic waste aggregates (kg/m^3) [39]

Mixture		FA100CWA0	FA100CWA25	FA100CWA75
Cement		360	360	360
Fly ash		160	160	160
Aggregate (0/4 mm)	NA	674	680	675
Aggregate (4/8 mm)	NA	380	285	95
Ceramic waste aggregate (4/8 mm)	CWA	0	95	285
Aggregate (8/16 mm)	NA	255	190	65
Ceramic waste aggregate (8/16 mm)	CWA	0	65	190
Water		233	319	370
Superplasticizer		4	4	4

Table 6. Properties in fresh and hardened state of the test mixtures containing ceramic waste aggregate and fly ash [39]

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	Compressive strength (MPa)
FA100CWA0	660	1.30	53.0
FA100CWA25	620	1.00	42.5
FA100CWA75	600	0.50	45.4

3.3. SCC mixtures with fly ash and ceramic waste aggregate

In the following SCC mixtures coarse aggregates (4/8 mm and 8/16 mm) were partially replaced with ceramic waste aggregates by 25% and 75% by mass. Bulk density of CWA was 815 kg/m^3. Cement type CEM II/A (S-L) 42.5R was used for the preparation of all mixtures, together with natural river aggregated separated in three standard fractions, fly ash from the thermal plant Kostolac and water. Superplasticizer was used in all concrete mixtures. Composition of the tested mixtures is presented in Table 5.

Slump flow test was performed in the fresh state, while compressive strength was tested in the hardened state. Results are presented in Table 6. Due to the higher water absorption of ceramic waste aggregate (16%), the



Figure 2. Samples of SCC concrete with ceramic waste aggregate after testing of compressive strength.

Table 7. Composition of the tested mixtures with polypropylene fibers and fly ash (kg/m^3)

Mixture		FA35FI0	FA35FI0.9	FA35FI1.2
Cement		330	330	330
Limestone filler		180	180	180
Fly ash		100	100	100
Aggregate (0/4 mm)	NA	840	840	840
Aggregate (4/8 mm)	NA	428.5	428.5	428.5
Aggregate (8/16 mm)	NA	428.5	428.5	428.5
Water		208	208	208
Polypropylene fibers		0	0.9	1.2
Superplasticizer		6.6	6.6	6.6

Table 8. Properties in fresh and hardened state of the test mixtures containing polypropylene fibers and fly ash

Length of fibers		Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength (MPa)	Water penetration depth (mm)
-	FA35FI0	775	5.0	21.64	0.88	58.8	12.17
6 mm	FA35FI0.9-6	705	9.0	23.89	0.82	62.5	10.28
	FA35FI1.2-6	662	10.5	22.63	0.71	56.6	16.38
40 mm	FA35FI0.9-40	745	5.0	23.80	0.91	57.1	11.20
	FA35FI1.2-40	770	4.7	22.00	0.91	58.8	10.88

total amount of water was higher in the mixtures containing this type of aggregate. Bulk density of the tested mixtures ranged between 2096 kg/m^3 and 2200 kg/m^3. The increase in CWA content led to decrease in slump flow diameter and time t_{500}, as well as to decrease in compressive strength. Nevertheless, the compressive strength of the samples containing higher amount of CWA was for 6.8% higher than the compressive strength of the samples containing 25% of CWA (Figure 2).

3.4. SCC mixtures with fly ash and polypropylene fibers

Fiber reinforced SCC concrete mixtures were prepared using monofilament polypropylene fibers of different length. One type of fibers was 90/40 with length of 6 mm and another with length of 40 mm. River aggregate separated in three standard fractions was used for concrete production. Cement CEM I 42.5R was used for the preparation of all mixtures, with limestone filler produced by Granit Pescar Ljig and fly ash from the thermal power plant Kolubara and water. Composition of the tested mixtures is presented in Table 7.

The addition of polypropylene fibers with length of 6 mm influenced reduction in slump flow diameter and increase in time t500 and V-funnel time. Bulk density of all mixtures ranged between 2286 kg/m^3 and 2326 kg/m^3. Mixture with higher percent of fibers with length of 40 mm performed very similar to reference mixture regarding all of the tested parameters in fresh and hardened state. All mixtures showed good resistance to water penetration (Table 8).

3.5. SCC mixtures with ground concrete

Materials used for concrete in these mixtures were: natural river aggregate, limestone powder and ground concrete (RCA), cement, chemical admixture and water. RCA powders were named fillers RA, RB and RC, originating from three types of ground concrete: normally vibrated concrete (RA), normally vibrated recycled concrete made with river sand and coarse aggregate that was combining river aggregate and RCA in amount of 50% (RB), and normally vibrated recycled concrete made with river sand and recycled concrete coarse aggregate (RC). Composition of the tested mixtures is presented in Table 9.

In these mixtures the quantity of aggregates was kept constant, together with the amount of cement. Testing results are presented in Table 10. All of the tested mixtures showed good properties, both in fresh and

Table 9. Composition of the tested mixtures with partial replacement of filler with ground concrete (kg/m^3) [40,41]

Mixture		R0LF100	RA50LF50	RB50LF50	RC50LF50
Cement		380			
Limestone filler		220	110	110	110
Mineral filler RA		0	110	0	0
Mineral filler RB		0	0	110	0
Mineral filler RC		0	0	0	110
Aggregate (0/4 mm)	NA	840	840	840	840
Aggregate (4/8 mm)	NA	430	430	430	430
Aggregate (8/16 mm)	NA	430	430	430	430
Water		183	183	183	183
Superplasticizer		7.6	7.6	7.6	7.6

Table 10. Properties in fresh and hardened state of the test mixtures containing ground concrete and fly ash as partial filler replacement [40,42]

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength (MPa)	Water penetration depth (mm)
R0LF100	761	2.62	9.73	0.97	58.7	16.3
RA50LF50	695	4.78	13.23	0.95	56.8	17.0
RB50LF50	720	4.85	11.90	0.95	56.1	17.3
RC50LF50	730	4.53	11.37	0.95	58.4	17.7

hardened state. The addition of all recycled mineral fillers led to decrease in workability and increase in viscosity, but did not affect the passing ability of the concrete mixtures [40]. All of the tested mixtures reached similar values of compressive strength at the age of 28 days.

3.6. SCC mixtures with recycled concrete aggregate (RCA) and crumbed rubber aggregates (CR)

The aim of these studies was to explore the influence of the recycled concrete aggregates and crumbed rubber on the physical and mechanical properties of the SCC mixtures.

Natural fine river aggregate was replaced with crumb rubber at two levels of volumetric replacement (20% and 30%), while the natural coarse aggregate was completely replaced by RCA. The RCA composition was as follows: 98% base concrete, 1.2% asphalt and 0.8% brick debris. Bulk density of the RCA was 1304 kg/m^3 for fraction 4/8 mm and 1342 kg/m^3 for fraction 8/16 mm, while bulk density of the crumbed rubber aggregate was 1120 kg/m^3. The cement used in this study was Portland-composite cement CEM II/A-M(S-L) 42,5R, together with limestone filler with particle size under 0.125 mm. Composition of the mixtures is presented in Table 11.

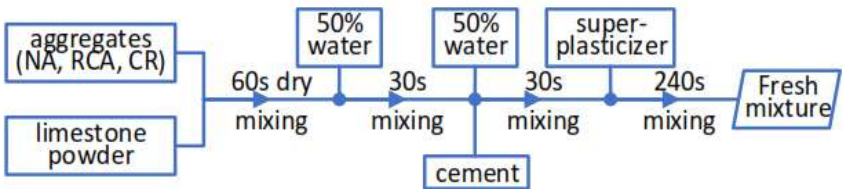


Figure 3. Schematic representation of the applied TSMA.

Table 11. Composition of the tested mixtures with recycled concrete aggregates and crumb rubber (kg/m^3) [43]

Mixture		REF	CR0C100	CR20C100	CR30C100
Cement		380			
Limestone powder		250			
Aggregate (0/4 mm)	NA	860	860	688	602
	CR	0	0	71.3	107
Aggregate (4/8 mm)	NA	530	0	0	0
	RCA	0	530	530	530
Aggregate (8/16 mm)	NA	310	0	0	0
	RCA	0	310	310	310
Water		171.0	199.6	199.6	199.6
Superplasticizer		4.4			

Table 12. Properties in fresh and hardened state of the test mixtures [43]

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength (MPa)	Water penetration depth (mm)
REF	840	2.2	9.3	0.99	50.4	12
CR0C100	790	2.4	12.4	0.88	51.9	27
CR20C100	770	3.1	13.4	0.88	39.6	28
CR30C100	730	3.5	16.6	0.85	29.2	32

Due to the higher water absorption of RCA (3% for fraction 4/8 mm and 4% for fraction 8/16 mm), mixtures containing this type of aggregate had higher amount of water, including water used for the saturation of the RCA grains. During the concrete production two-stage mixing approach (TSMA) was used, as shown in Figure 3.

Obtained results are summarized in Table 12. The flowability of the mixtures decreased while viscosity increased with the increase of CR content and replacement of natural aggregates with RCA. Mixture CR30C100 reached SF2 flowability class, while other mixtures were classified as SF4 class. All tested mixtures were classified as VS2/VF2 class according to flow time and V-funnel tests. The replacement of NA with RCA lead to the reduction of passing ability by



Figure 4. Fracture surface of hardened concrete with addition of crumbed rubber aggregate and recycled concrete aggregate.

Table 13. Composition of the tested mixtures with crumbed rubber and polypropylene fibers (kg/m^3)

Mixture		FI0CR0	FI0CR10	FI0.8CR0	FI0CR30	FI0.8CR30
Cement		380				
Limestone filler		180				
Aggregate (0/4 mm)	NA	877	789.3	877	613.9	613.9
Crumbed rubber (0/4 mm)	CR	0	43.1	0	129.4	129.4
Aggregate (4/8 mm)	NA	158.5	158.5	158.5	158.5	158.5
Aggregate (8/16 mm)	NA	565.8	565.8	567.8	565.8	565.8
Water		212.8	205.2	212.8	186.2	205.2
Polypropylene fibers		0	0	0.8	0	0.8
Superplasticizer		3.04	3.80	3.80	5.7	4.56
Viscosity modifier		2.28				

Table 14. Properties in fresh and hardened state of the test mixtures containing crumbed rubber aggregate and polypropylen fibers

	Slump flow diameter (mm)	Slump flow time t_{500} (s)	V-funnel time (s)	L-box PA (/)	Compressive strength (MPa)
FI0CR0	620	2.03	5.26	0.47	40.9
FI0CR10	745	2.10	5.56	0.64	34.8
FI0.8CR0	630	2.27	6.42	0.51	45.3
FI0CR30	735	2.91	9.90	0.54	27.6
FI0.8CR30	585	5.60	9.26	0.33	24.2

11%, while addition of CR did not influence this property. Bulk density of the mixtures ranged between 2207 kg/m^3 and 2405 kg/m^3. The coarse RCA did not affect compressive strength values, while CR addition has considerably decreased this property. The addition of RCA and CR significantly increased the water permeability, even up to 167% for the highest level of replacement. Still, mixtures with CR replacement level up to 20% were classified as impermeable under aggressive conditions.

3.7. SCC mixtures with crumbed rubber aggregate and polypropylene fibers

In the following study fine aggregates (0/4 mm) were partially replaced with crumbed rubber. In addition, some of the mixtures were prepared using monofilament polypropylene fibers. Cement type CEM II/B (V-L) 42.5R was used for the preparation of all mixtures, together with natural river aggregate separated into three standard fractions, limestone filler with maximal grain size of 0.125 mm, and water. Composition of the tested mixtures is presented in Table 13.

All mixtures containing crumbed rubber were designed to achieve slump flow diameter of approximately 700±50 mm. Therefore the amount of superplasticizer was increased with increase in rubber content, with reduction of water content. The addition of polypropylene fibers in the mixture FI0.8CR0 increased the neccessary amount of the superplasticizer, but did not induce reduction of water. In the case of mixture FI0.8CR30 the amount of superplasticizer was lower than for the mixture FI0CR30, but the neccessary amount of water increased for 10.2%. Bulk density in fresh state varied between 2200 kg/m^3 and 2343 kg/m^3 The obtained testing results for fresh and hardened state are presented in Table 14.

The addition of crumbed rubber led to increase in both V-funnel time and slump flow time. Also, segregation of rubber aggregates was noticeable on the surfaces of the tested mixtures in fresh state. It was also concluded that the addition of rubber lead to decrease in compressive strength of the tested concrete samples at the age of 28 days. Still, as expected, the increase in rubber content led to increase in impact resistance of the hardened concrete. The fracture surface of hardened

concrete containing crumbed rubber aggregate is shown in Figure 5.

4. RESULT ANALYSIS

In order to compare the amounts of the materials used for the presented SCC mixtures, especially related to the amount of recycled or waste materials used, mixtures were divided into two groups. In the first group, mixtures containing recycled and waste materials as partial replacement of filler or cement were presented in Figure 6. In Figure 7, the second group of mixtures containing recycled materials used as partial replacement of aggregates were presented.

The total amount of fine particles was similar in all mixtures of the first group, ranging between 520 kg/m^3, up to 600 kg/m^3. The lowest amount of cement was used for mixture FA35FI0, while the highest amount of fly ash was applied in the mixture FA100F0C0. In the second group, the highest quantity of fine particles was used for the mixtures containing only cement and limestone filler (630 kg//m^3).

The highest amount of recycled and waste materials was used for the mixture FA100F100C100, where fly ash was used as filler component, and RCA as total replacement for both fine and coarse aggregates. Most of the mixtures presented in Figure 7 had coarse aggregate completely replaced with one or more types of recycled aggregates.

Comparisson of the fresh state propreties of the different SCC mixtures was performed for the slump flow time measurements (Figure 8) and V-funnel time measurements (Figure 9).

It can be noticed that most of the tested mixtures were classified as VF2, while approximately 30% of the tested mixtures fulfilled the requirements for the class VS1. It was again confirmed that the properties of the SCC in fresh state cannot be analysed using only one of the standardized testing methods. The slump flow diameter was not taken into account in this analysis because it was, in some cases, used as a target value during the mixture design process.

Mixtures containing fly ash showed on the whole higher flowability and higher viscosity, since the obtained



Figure 5. Fracture surface of hardened SCC with addition of crumbed rubber aggregate.

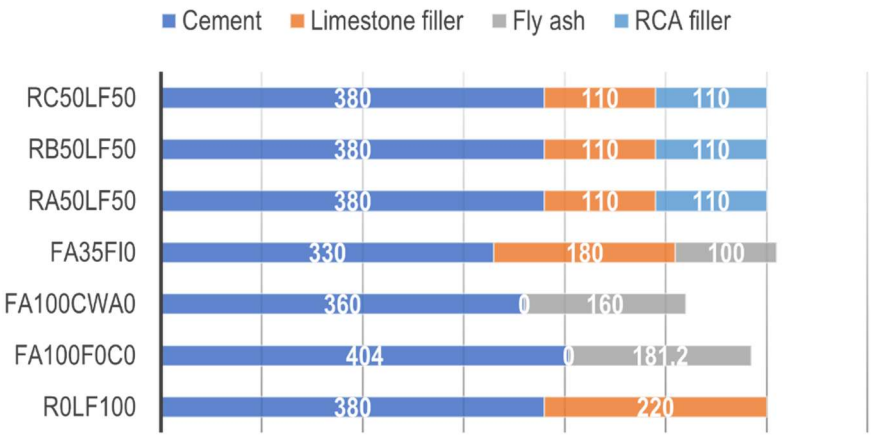


Figure 6. Comparisson of the amount of the fines (cement+mineral additives) in different SCC mixtures (Group I)

results led to reduction of t500 times and increase of V-funnel times for these mixtures. The highest viscosity was measured for the mixture containing 50% of fine aggregates replaced with RCA. When both fine and coarse aggregates were completely replaced by RCA, improved results concerning V-funnel time were obtained.

Although it was mentioned in the literature, the negative influence of the fly ash on the passing ability of the SCC mix, was not pronounced. It was concluded that the addition of fibers, especially when combined with crumbed rubber aggregate led to reduction of passing ability up to the 50%. Blocking effect was not noticed for these mixtures.

Reduced flowability of mixtures containing RCA as 50% of filler replacement was confirmed through the experimental results, but the viscosity of these mixtures was increased for 15% to 35% depending on the type of ground RCA used.

Comparison of the compressive strength values was presented in Figure 10. The highest value of compressive strength was obtained for the mixture FA100F0C0 with fly ash used as a filler, reaching almost 80 MPa. Since this was the mixture with highest amount of cement, and prepared with only natural

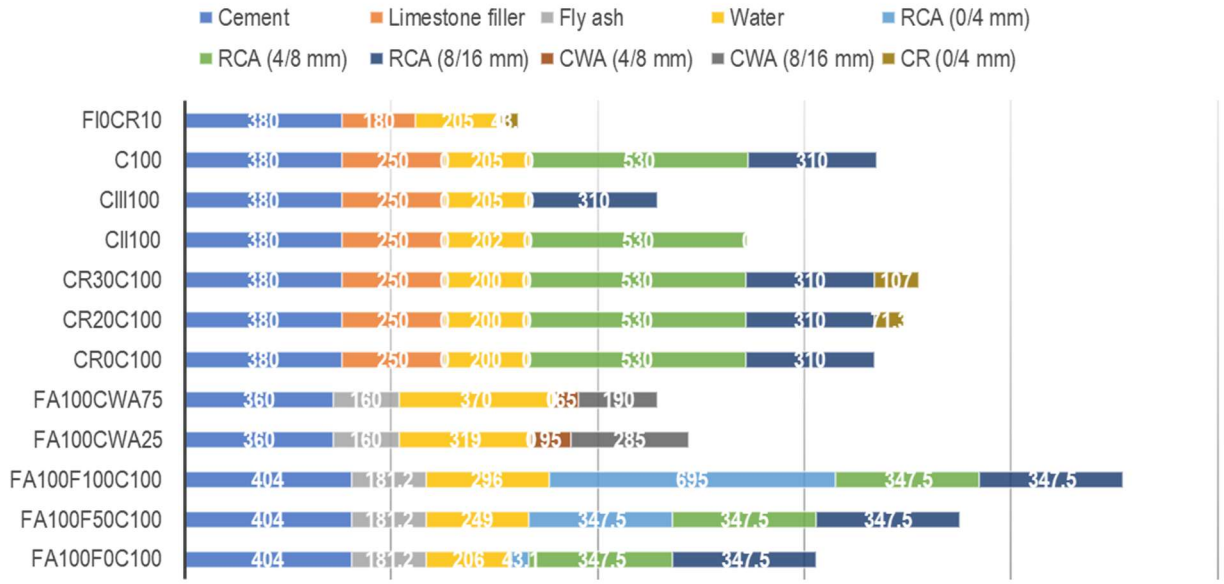


Figure 7. Comparisson of the amount of the applied recycled concrete aggregate in SCC mixtures (Group II).

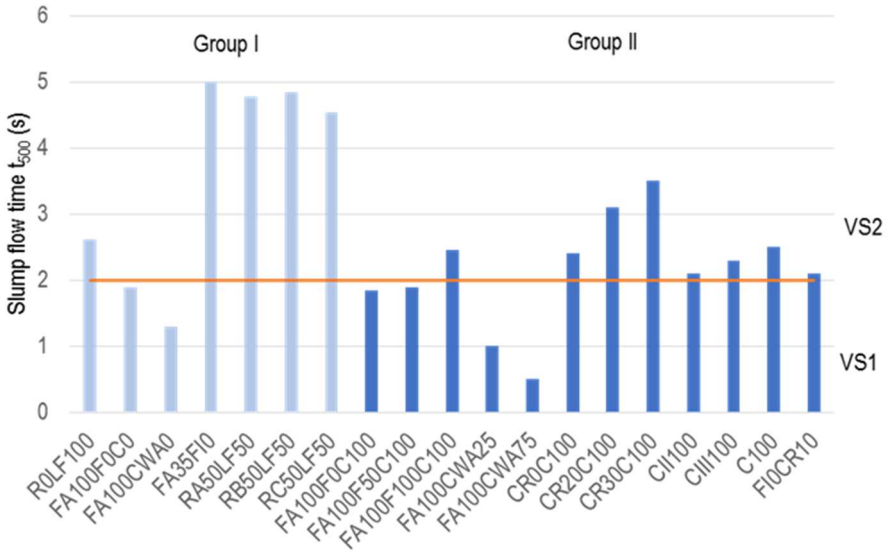


Figure 8. Comparisson of the time t500 measured for different SCC mixtures.

aggregates, the results are expected. The lowest values of compressive strength were achieved for the mixtures containing crumbed rubber as aggregate, as well as for mixtures containing ceramic aggregates, which was also expected due to the previous results from the literature.

Water permeabilty was measured for the majority of mixtures, with very positive results. Most of the tested mixtures had water permeability depth lower than 20 mm, the only exeption being the mixtures with addition of crumbed rubber aggregates, that led to the increase of this value. The results are expected considering the higher amount of fine particles in the SCC concrete that improve the density of its structure.

5. CONCLUSION

The paper presents testing results of the fresh and hardened state of SCC mixtures prepared using different waste and recycled materials, such as fly ash, ground recycled concrete, recycled concrete aggregate, ceramic recycled aggregates, crumbed rubber and recycled fibers. The results were obtained as a part of continuing research in this area conducted in the Laboratory of materials, Faculty of Civil Engineering, University of Belgrade.

The obtained results confirm that the use of recycled and waste materials in SCC production is possible and promising. According to the performed tests, it was possible to obtain the class VS2 and VF1 in the mixtures where total amount of coarse aggregates was replaced with RCA. Also, very good hardened state properties, were obtained on mixtures containing RCA with high water absorption (up to 16%).The compressive strength results ranged between 29.2 MPa for mixture containing 30% of crumbed rubber as fine aggregate replacement and 74.0 MPa with filler component replaced with fly ash. Presented results confirm that both cements CEM I and CEM II provide high mechanical properties of SCC. Mixtures designed using particle packing method showed the overall highest mechanical properties and low water permeability, but at the same time required the highest amount of cement. In the mixtures with complete coarse aggregates

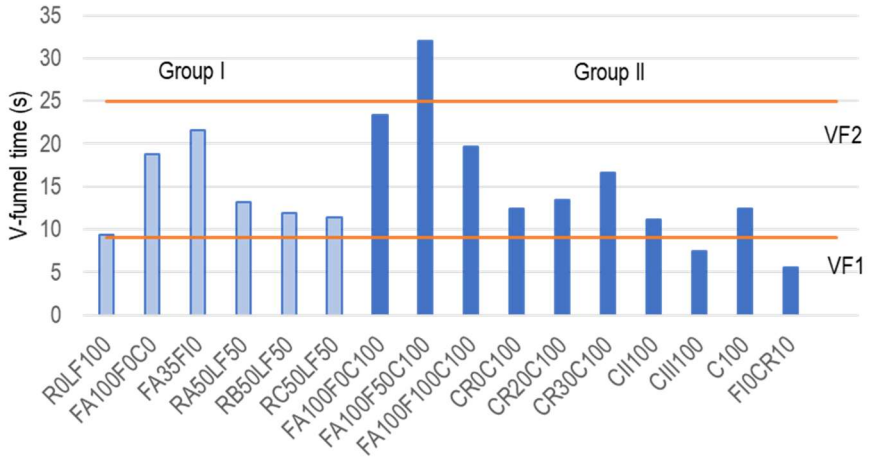


Figure 9. Comparisson of the V-funnel time measured for different SCC mixtures.

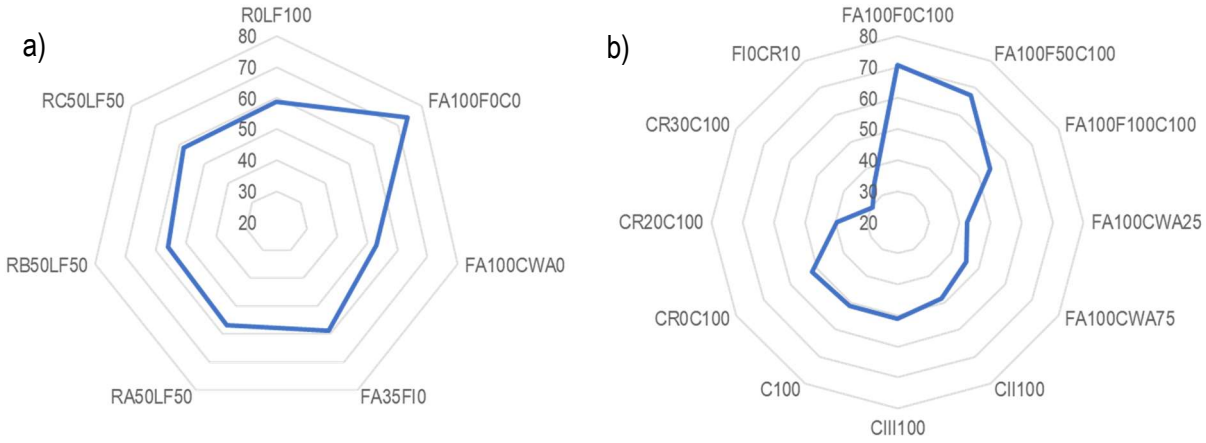


Figure 10. Comparisson of compressive strength results of the tested mixtures at the age of 28 days: a) Group I, b) Group II.

replaced by RCA, the compressive strength of 50.1 MPa was reached, showing that it is possible to obtain higher classes of concrete using this type of aggregates.

The results also underline the importance of defining the fresh state properties of SCC using several different testing methods. This approach needs to be incorporated in the large-scale application of this type of material.

Apart from the results of water permeability presented in this paper, other durability tests such as chloride penetration depth, carbonation resistance and frost resistance should be performed before the final receipt definition, if the concrete is to be placed in elements that are exposed to different environmental conditions.

Commitment to green technologies, such as the use of secondary raw materials, energy saving, and CO_2 emission reduction, must remain in focus when applied to self-compacting concrete.

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33. SLOVENSKI KOLOKVIJ O BETONIH

Primjena samozbijajućeg betona u Hrvatskoj

Application of self-compacting concrete in Croatia

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Sažetak

U radu su prikazana dva primjera primjene samozbijajućeg betona u Hrvatskoj. Prvi se odnosi na sanaciju mosta kopno – otok Vir, gdje je zbog korozije armature provedena obnova mosta od 1998. do 2003. godine. SCC je korišten pri obnovi donjih pojasnica nosača i naglavnica stupova jer je omogućio kvalitetno ispunjavanje oplate i prostora oko armature bez dodatnog zbijanja. Drugi primjer prikazuje obnovu HE Dubrovnik u Platu kod Cavtata, gdje je samozbijajući beton korišten pri zamjeni usisne cijevi agregata. Zbog ograničenog prostora oko cijevi nije bilo moguće koristiti klasični vibrirani beton, pa je SCC bio optimalno rješenje. Prethodnim ispitivanjima potvrđena su tražena svojstva svježeg i očvrsnulog betona. Zaključno, samozbijajući beton predstavlja učinkovito rješenje za složene građevinske zahvate, ali zahtijeva pažljivo projektiranje sastava, kontrolu proizvodnje i pravilnu tehnologiju ugradnje.

Abstract

The c The paper presents two examples of the application of self-compacting concrete in Croatia. The first refers to the rehabilitation of the mainland–Vir Island bridge, where the bridge was renovated from 1998 to 2003 due to reinforcement corrosion. SCC was used in the repair of the lower girder flanges and pier cap beams because it enabled high-quality filling of the formwork and the space around the reinforcement without additional compaction. The second example describes the reconstruction of Dubrovnik Hydropower Plant in Plat near Cavtat, where self-compacting concrete was used during the replacement of the turbine draft tube. Due to the limited space around the pipe, it was not possible to use conventional vibrated concrete, so SCC proved to be the optimal solution. Preliminary testing confirmed the required properties of both fresh and hardened concrete. In conclusion, self-compacting concrete represents an effective solution for complex construction works, but it requires careful mix design, production control, and proper placing technology.

Ključne riječi: samozbijajući beton, sanacija mosta, nedostupna mjesta
Keywords: self-compacting concrete, bridge rehabilitation, inaccessible places

1. UVOD

Samozbijajući beton (eng. Self Compacting Concrete) je specijalna vrsta betona koja se razlikuje od običnog betona prvenstveno u svojstvima u svježem stanju: tečenje, viskoznost i sposobnost obilaženja prepreka. Kako mu i samo ime kaže prilikom ugradnje nije ga potrebno zbijati, već se on zbija pod vlastitom težinom. Razvijen je u Japanu krajem 80tih godina. Kako bi se poboljšala trajnost betona i smanjile greške u izvođenju profesor Okamura je razvio beton koji se zbija pod vlastitom težinom, popunjava prostor između armature i teško dostupnih mjesta. [1, 2]

Prilikom gradnje svjetskih značajnih građevina, koristio se samozbijajući beton kao na primjer Øresund Bridge koji spaja Dansku i Švedski ili naš Most Pelješac koji je teritorijalno spojio jug Hrvatske s ostatkom zemlje.

Samozbijajući beton ima puno prednosti, a možda i najveći nedostatak mu je velika osjetljivost na male varijacije u sastavu betona, odnosno, vrlo male promjene u sastavu značajno mijenjaju svojstva u svježem stanju, dok će svojstva u očvrsnulom stanju u većini slučajeva biti zadovoljena (osim ako nisu zadani vrlo visoki kriteriji).

2. PRIMJENA SAMOZBIJAJUĆEG BETONA KOD SANACIJE MOSTA KOPNO – OTOK VIR

U Hrvatskoj su prvi primjeri primjene samozbijajućeg betona bili početkom 2000.-tih. Tijekom sanacije mosta kopno - otok Vir (Slika 1) koji je pušten u promet 26.4.1976., u razdoblju od 1998. do 2003. godine obnavljani su svi elementi mosta jer je korozija armature uzrokovana difuzijom kloridnih iona uznapredovala i most je bio značajno oštećen (Slika 2).

Most je saniran betonom koji je bio modificiran stiren-butadijenskim lateksom uz dodatak polipropilenskih vlakana, a radovi su se izvodili pod naizmjeničnim prometom u više faza. [3] Obnova prednapetih nosača (dva u poprečnom presjeku), provodila se u kampadama. Donja pojasnica I-nosača obnovljena je samozbijajućim betonom tako da se beton ulijevao s jedne strane u oplatu, dok nije došao na drugu stranu van. Utvrđivanje sastava betona provedeno je u Laboratoriju Zavoda za materijale na Građevinskom fakultetu u Zagrebu, a provjera tehnologije je provedena u probnom polju na mostu u 10. rasponu. Izvedba probnog polja i sanacija mosta prikazani su na slikama 3 do 6.

Sastav samozbijajućeg betona kao i upute za pripremu betona za popravak donje pojasnice nosača su dane u nastavku i u tablici 1.

Započeti miješanje s ~2/3 količine vode i oba dodatka (miješati 4-5 minuta), a ostatak vode postepeno dozirati s polimerom. Navedena je količina vode za potpuno suhi pijesak.

Nakon doziranja polimera, beton miješati još najviše 30 sec. Na slici 7. prikazan je obnovljeni nosač i poprečni nosač u polju.



Slika 1. Most kopno – otok Vir



Slika 2. Korozija zaštitne cijevi kabela za prednapinjanje u nosaču mosta.



Slika 3. Priprema za izvedbu probnog polja na 10. nosaču



Slika 4. Postavljanje oplate za popravak donjeg pojasa južnog nosača u 10. polju

Tablica 1 Samozbijajući beton za obnovu donje pojasnice nosača (izvođenje u oplati).

	Sastav morta prije dodavanja polimera	Sastav morta nakon dodavanja polimera
cement PC 15z 45B (kg/m^3)	520	
voda (ako je potpuno suhi agregat) (L/m^3)	140	60
polimer (50 % suh.tv.) (L/m^3)		40
dodatak ViscoCrete* (%/mcementa)	0,50	
dodatak frostschutz ** (%/mcementa)	0,75	
vlakna L/d=10/0,02 mm (kg/m^3)	0,75	
pijesak 0 – 4 mm (kg/m^3) **4 – 8 mm (kg/m^3)**	850 560	
vrijeme miješanja	4-5 min	30 sec

* dodatak superplastifikatora za samozbijajući beton SIKA ViscoCrete 5-800
** dodatak za zimsko betoniranje SIKA Frostschutz (FS)

Prednapete naglavnice na stupovima također su bile sanirane samozbijajućim betonom čiji sastav je prikazan u tablici 2. i u nastavku su dane upute za miješanje.

Započeti miješanje s ~2/3 količine vode i oba dodatka (miješati 4-5 minuta), a ostatak vode postepeno dozirati s polimerom. Navedena je količina vode za potpuno suhi pijesak.

Nakon doziranja polimera, beton miješati još 30 sec.

Nakon obnove koja je završila 2003. godine, most je i danas u funkciji i upravo je proslavio 60. rođendan.



Slika 5. Ugradnja samozbijajućeg betona u donju pojasnicu nosača



Slika 6. Radovi u kampadama kod popravka Virskog mosta.



Slika 7. Obnova naglavnice stupa

Tablica 2. Samozbijajući beton za prednapete naglavnice (izvođenje u oplati)

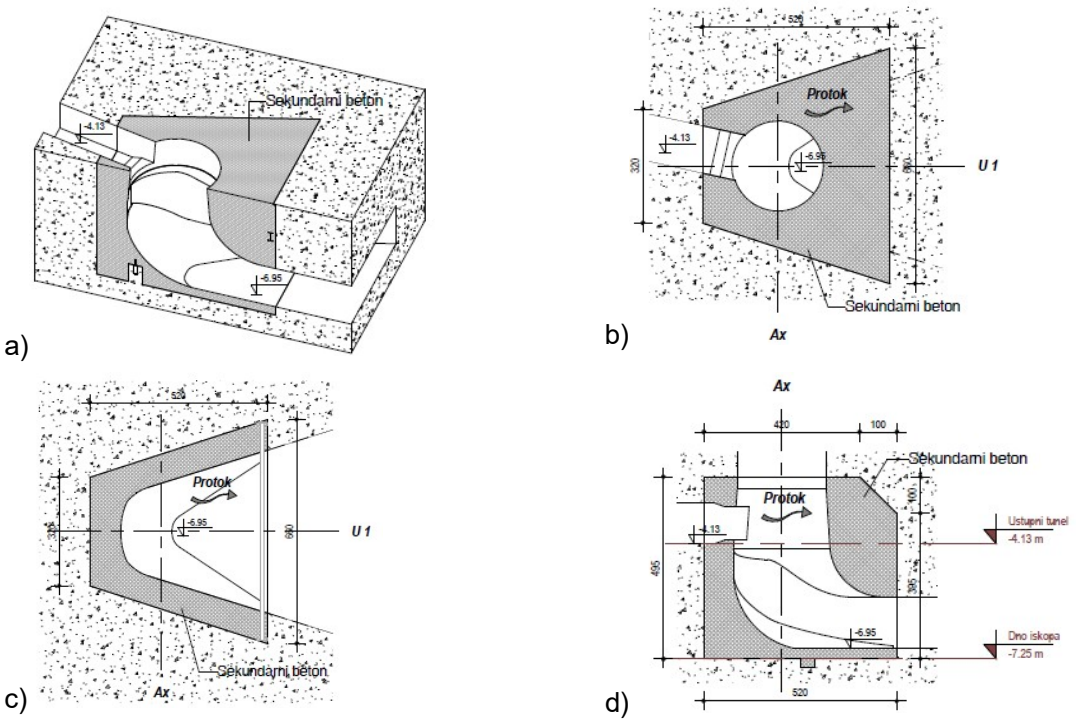
	Sastav morta prije dodavanja polimera	Sastav morta nakon dodavanja polimera
cement PC 15z 45B (kg/m^3)	430	
voda (ako je potpuno suhi pijesak) (L/m^3)	100	50
polimer (50 % suh.tv.) (L/m^3)		43
dodatak ViscoCrete* (%/mcementa)	0,50	
vlakna L/d=10/0,02 mm (kg/m^3)	0,75	
agregat 0 – 4 mm (kg/m^3) **4 – 8 mm (kg/m^3)** **8 – 16 mm (kg/m^3)**	900 250 490	
vrijeme miješanja	4-5 min	30 sec

* dodatak superplastifikatora za samozbijajući beton SIKA ViscoCrete 5-800

3. PRIMJENA SAMOZBIJAJUĆEG BETONA KOD OBNOVE HE DUBROVNIK U PLATU PORED CAVTATA

Obnova hidroelektrane Dubrovnik u mjestu Plat trajala je od 2011. do 2016. godine, tijekom koje je povećana snaga agregata za proizvodnju električne energije. U sklopu obnove agregata zamijenjena je i usisna cijev agregata. Zbog postizanja odgovarajuće stabilnosti i otpornosti na dinamička opterećenja, prostor oko cijevi se puni betonom. Zbog ograničenog pristupa u području ispod i oko usisne cijevi nije bilo moguće ugraditi uobičajeni vibrirani beton pa je zbog toga primijenjen posebni samozbijajući beton. [4]

Planom kvalitete izvedbe betonskih radova definirane su specifikacije za svojstva svježeg i očvrsnulog betona međutim, budući da je tehnologija samozbijajućeg betona rijetko u primjeni u Republici Hrvatskoj, mali je broj proizvođača betona koji imaju iskustva s projektiranjem sastava i proizvodnjom takve vrste



Slika 8. Prikaz područja oko usisne cijevi koje se ispunjava betonom (sivo): a) pogled: b) tlocrt na visini -4,13 m; c) tlocrt na visini -5,6m; d) presjek [4].

Tablica 3. Svojstva betona zahtijevana u PKI [5].

OSNOVNI UVJETI		
Svojstvo	**Razred**	**Metoda ispitivanja**
Razred tlačne čvrstoće	C 35/45	HRN EN 12390-3:2009
Razred izloženosti	XC2, XS2	
VDP	VDP 2	HRN EN 12390-8:2009
Konzistencija slijeganjem	S5	HRN EN 12350-2:2009
Maksimalno zrno agregata, D_{max}	16	
Razred sadržaja klorida	Cl^- 0,40	
DODATNI UVJETI		
Rasprostiranje slijeganjem	SF2 (660-750 mm)	HRN EN 12350 – 8:2010
Vrijeme t_{500}	VS2 (>2 s)	HRN EN 12350 – 8:2010
***J*-prsten**	PJ1 (12 šipki ≤10 mm)	HRN EN 12350 – 12:2010

materijala. Radi toga su provedena prethodna ispitivanja kako bi se primjenom lokalno dostupnih materijala, u prvom redu punila i agregata, ispunili zahtjevi traženi planom kvalitete izvedbe. Prethodna ispitivanja obuhvatila su optimizaciju sastava i svojstava samozbijajućeg betona u laboratoriju i na betonari te utjecaj transporta na svojstva svježeg betona. Opisani su i uspoređeni rezultati prethodnih ispitivanja sa ispitivanjima svojstava svježeg betona na mjestu ugradnje u HE Dubrovnik te ispitivanjima uzoraka očvrsnulog betona uzetih na mjestu ugradnje pri zamjeni prve usisne cijevi. Također su prikazani i rezultati početnog ispitivanja tipa na betonari jer je trebalo ishoditi Izjavu o svojstvima za novu vrstu betona za tu betonaru.

3.1. Opis zahvata

HE Dubrovnik koristi vodu rijeke Trebišnjce iz akumulacijskog jezera Bileća, nastalo izgradnjom brane Grančarevo.

Nakon što prođe kroz rotor turbine, voda otječe kroz usisnu cijev (difuzor). Namjena usisne cijevi je smanjenje izlazne brzine vode, čime se smanjuju izlazni gubici energije, a time povećava ukupna korisnost turbine. Pri prolazu kroz difuzor, voda mijenja smjer strujanja iz vertikalnog u horizontalni i otječe u nizvodni bazen. Na slici 8 prikazano je područje oko usisne cijevi koje se ispunjava betonom. Usisna cijev na izlazu vode iz turbine je kružnog profila. S udaljavanjem od rotora profil cijevi se postepeno povećava i prelazi iz kružnog u pravokutni.

Sa slike 8d može se uočiti da je udaljenost između dna usisne cijevi i dna iskopa 30 cm zbog čega nije moguće provoditi vibriranje betona. Kako bi bila osigurana kvalitetna ugradnja betona u prostor oko cijevi te kako bi se postigla adekvatna zbijenost betona i obavijanje armature primijenjena je tehnologija samozbijajućeg betona.

Planom betoniranja prostora oko jedne cijevi predviđeno je da se betoniranje provede u 11 slojeva. Izabrana je relativno mala visina pojedinog sloja od 40 cm iz razloga da prilikom betoniranja uzgon betona ne uzrokuje pomake cijevi veće od dopuštenih te da se ograniči porast temperature betona uzrokovan hidratacijom cementa.



a) b)

Slika 9. a) Betonara; b) natkriveni separator za frakcije agregata.

Tablica 4. Predloženi sastav samozbijajućeg betona za dobetoniranje usisne cijevi [6].

Komponenta	Masa, kg
cement: CEM II/B-M (S-L) 42,5N	400
voda (v/c = 0,41)	165
kem. dodatak: GLENIUM 51	5,2 - 5,6*
punilo: VAPNENAC	200
agregat (VAPNENAC): 0-4 (55%), 4-8 (19,3%), 8-16 (25,7%)	1491,4

* ovisno o načinu doziranja pojedinih sastojaka i vremenu miješanja

Tablica 5. Rezultati prethodnih (u laboratoriju) te početnih (na betonari) ispitivanja svojstava samozbijajućeg betona u svježem stanju.

Svojstvo	Kriterij prema PKI	Laboratorij	Betonara	
Slijeganje rasprostiranjem, mm	660-750	735	**610***	700**
Vrijeme t_{500}, s	≥ 2	**0,6**	1,56*	1,03**
Mjera J-prstena, mm	≤ 10 (12 šipki)	10	nije izmjeren	10**

* prije smanjenja količine punila; ** nakon smanjenja količine punila

3.2. Zahtjevi za beton

Prema Panu kvalitete izvedbe betonske konstrukcije (PKI) [5] u tablici 3 navedeni su zahtjevi za svojstva betona u svježem i očvrsnulom stanju.

U svrhu određivanja sastava betona s traženim svojstvima provedena su: prethodna ispitivanja u Laboratoriju za materijale na Građevinskom fakultetu u Zagrebu, početno ispitivanje tipa na betonari (Slika 9) koja je bila u relativnoj blizini gradilišta, a imala je kapacitete da proizvodi novu vrstu betona sa specijalnim zahtjevima u svježem stanju te probno ispitivanje betona na mjestu ugradnje u HE Dubrovnik. Nakon provedbe prethodnih, početnih i probnih ispitivanja započela je faza izvođenja radova na betoniranju usisne cijevi. [6]

3.2. Rezultati ispitivanja

Predložen je sastav samozbijajućeg betona dan u tablici 4, s osnovnim ciljem da se maksimalno iskoriste lokalno dostupni materijali. Rezultati ispitivanja svojstava svježeg betona prikazani su u tablici 5. Vidljivo je da je došlo do blage korekcije u sastavu betona, ali sve u skladu sa zahtjevima iz PKI.

Na slici 10 prikazana su ispitivanja svojstava u svježem stanju provedena u laboratoriju. [6]

S obzirom na tip mješalice u laboratoriju i betonari, korigirana je i podešena procedura miješanja betona na



a) b) c)

Slika 10. Ispitivanje u laboratoriju: a) vremena t_{500} , b) rasprostiranja slijeganjem i c) mjere J-prstena [6].

Tablica 6. Rezultati ispitivanja samozbijajućeg betona u očvrsnulom stanju nakon 28 dana na uzorcima uzetih tijekom prethodnih, početnih i probnih ispitivanja.

Svojstvo	Kriterij prema PKI	Laboratorij	Betonara	Probno ispitivanje na mjestu ugradnje
Tlačna čvrstoća, MPa	C 35/45	61,2 ± 2,9	55,3 ± 0,2	61,6±1,1
Vodonepropusnost, mm	VDP 2 (max. prodor 15-30 mm)	14	14	nije ispitano

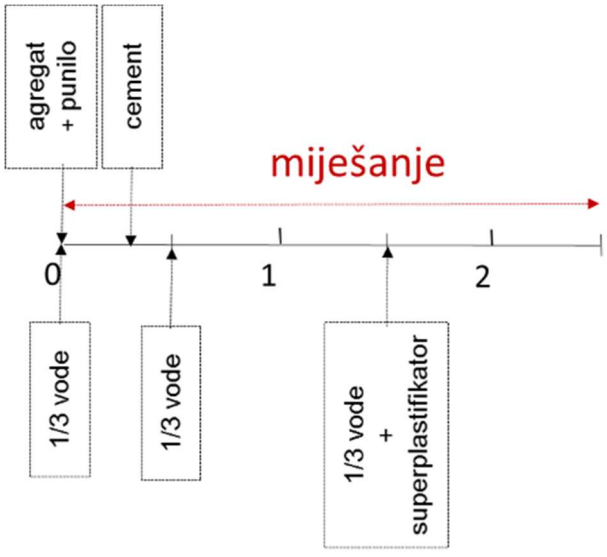
betonari, kako bi nakon transporta , beton na mjestu ugradnje imao zahtijevana svojstva prema tablici 3. Slika 11 prikazuje korigiranu proceduru miješanja betona na betonari. [6]

U tablici 6 su dani rezultati ispitivanja svojstava samozbijajućeg betona u očvrsnulom stanju na uzorcima uzetim tijekom prethodnih, početnih i probnih ispitivanja. Ispitivanja uzoraka uzetih na betonari su provedena samo za mješavinu koja je napravljena nakon optimizacije, tj. s manjom količinom punila. Rezultati tlačne čvrstoće, prikazani u tablici 6, predstavljaju srednju vrijednost ispitivanja s iskazanom standardnom devijacijom. Na temelju tih rezultata može se zaključiti kako je kriterij za razred tlačne čvrstoće C35/45 ispunjen. Rezultati ispitivanja vodonepropusnosti odnose se na najveću dubinu prodora vode u uzorak i pokazuju da projektirana mješavina zadovoljava kriterije koji se postavljaju i za strožiji razred vodonepropusnosti, VDP 1.

Na temelju probnog ispitivanja definiran je proces modifikacije obradljivosti betona superplastifikatorom te je dokazano da je moguće modificirati svojstva dostavljenog betona na mjestu ugradnje u dovoljnoj mjeri da ona zadovolje kriterije zadane u PKI. Provedbom prethodnih, početnih i probnih ispitivanja prikupljene su informacije potrebne za ostvarivanje primjene samozbijajućeg betona pri betoniranju usisne cijevi.

4. ZAKLJUČAK

U ovom radu prikazana su dva primjera primjene samozbijajućeg betona koji je jedna od specijalnih vrsta betona. U praksi izvođači često govore da ugrađuju samozbijajući beton, ali pri tome ne kontroliraju neophodna svojstva kao tečenje, viskoznost i sposobnost obilaženja prepreka, pa se i ne može govoriti o ugradnji samozbijajućeg betona, ako se kontrolira konzistencija samo pomoću metode slijeganja. Prikazani primjeri pokazuju sposobnost građevinske industrije da proizvede i ugradi samozbijajući beton i kod izvedbe novih građevina, kao i kod sanacije postojećih. Samozbijajući beton ima budućnost samo treba vrlo pažljivo provjeriti sve faze primjenjenih tehnologija ugradnje kako nedovoljna



Slika 11. Nova procedura miješanja (min) samozbijajućeg betona na betonari .

priprema i podešavanje sastava betona i miješanja ne bi uzrokovala oštećenja u konstrukciji.

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33. SLOVENSKI KOLOKVIJ O BETONIH

Rehabilitation of a Reinforced-Concrete Deep-Water Intake Tower Using Polyurethane Injection and Self- Compacting Concrete Ring Strengthening

Sanacija stolpa za zajem globoke vode iz armiranega betona z injiciranjem poliuretana in ojačitvijo z obroči iz samozgoščevalnega betona

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Abstract

This paper presents the rehabilitation of a reinforced-concrete deep-water intake tower at Lake Batllava, Kosovo, which used as part of the regional drinking-water supply infrastructure. The structure developed severe leakage at approximately 22 m below the water level over nearly three-quarters of its circumference, accompanied by visible cracking and measurable deviation from verticality. The damage was identify during the winter period, specifically under the ice action in combination with severe hydraulic exposure conditions. The adopted intervention followed a staged rehabilitation strategy in which active leakage was first brought under control, after which the damaged belt was repaired and structurally strengthened. Local pressure reduction was used to create workable conditions in the critical zone; cracks were prepared in a controlled V-shaped profile, seepage was arrested using a rapid-setting water-stopping mortar, and the leakage paths were sealed by polyurethane injection. After watertightness had been restored, the tower was strengthened using reinforced self-compacting concrete (SCC) rings connected to the existing structure. Three SCC trial mixtures were developed and tested to verify filling ability, passing ability, and segregation resistance under difficult pumping and placement conditions. The case demonstrates that the successful rehabilitation of underwater hydraulic concrete structures depends on correct intervention sequencing, compatibility between sealing and strengthening measures, and constructability-oriented material selection.

Povzetek

V tem članku je predstavljena sanacija stolpa za zajem globoke vode iz armiranega betona ob jezeru Batllava na Kosovu, ki se uporablja kot del regionalne infrastrukture za oskrbo s pitno vodo. Na objektu se je približno 22 metrov pod gladino vode pojavilo hudo puščanje, ki je zajemalo skoraj tri četrtine njegovega obsega, spremljale pa so ga vidne razpoke in merljivo odstopanje od navpičnice. Poškodbe so bile ugotovljene v zimskem obdobju, zlasti zaradi delovanja ledu v kombinaciji z izjemno hidravlično izpostavljenostjo. Izvedeni poseg je potekal v skladu s postopno strategijo sanacije, v okviru katere so najprej obvladali aktivno puščanje, nato pa so poškodovani pas popravili in ga konstrukcijsko ojačili. Za vzpostavitev primernih delovnih pogojev v kritičnem območju smo uporabili lokalno zmanjšanje tlaka; razpoke smo pripravili v nadzorovanem V-oblikovanem profilu, pronicanje vode smo ustavili z hitro strjujočo malto za zaustavitev vode, poti pronicanja pa smo zatesnili z injiciranjem poliuretana. Po ponovni vzpostavitvi neprepustnosti za vodo je bil stolp ojačan z obroči iz armiranega samozgoščevalnega betona (SCC), ki so bili povezani z obstoječo konstrukcijo. Razvili in preizkusili smo tri poskusne mešanice SCC, da bi preverili njihovo sposobnost zapolnjevanja, prehodnost in odpornost proti segregaciji v zahtevnih pogojih črpanja in vgrajevanja. Ta primer kaže, da je uspešna sanacija podvodnih hidravličnih betonskih objektov odvisna od pravilnega zaporedja posegov, skladnosti med ukrepi za tesnjenje in ojačitev ter izbire materialov, ki so primerni za gradnjo.

Keywords: Intake tower; Hydraulic Structure; Leakage repair; Polyurethane injection; self-compacting concrete; ring strengthening; ice action

Ključne besede: zbirni stolp; hidravlična konstrukcija; sanacija puščanja; injektiranje poliuretana; samozgoščevalni beton; ojačitev obroča; delovanje ledu

1. INTRODUCTION

Underwater hydraulic structures operate under severe environmental and mechanical exposure conditions while often remaining in service for several decades with limited access for routine inspection, maintenance, or direct intervention. Intake towers, outlet structures, and associated reinforced-concrete components are continuously exposed to hydrostatic pressure, long-term material aging, repeated wetting-drying cycles, thermal fluctuations, and, in cold regions, freeze-thaw and ice-induced actions. These combined effects may progressively impair both watertightness and structural stiffness. Once cracking, leakage, and local deformation develop simultaneously, the consequences may extend beyond localized material deterioration and can directly threaten the operational continuity, durability, and safety of strategic water-supply infrastructure [(Wang et al., 2025;Hellgren et al., 2022; Lv et al., 2024)].

Recent research has shown that the rehabilitation of underwater concrete structures is governed not only by the damage mechanism itself, but also by the feasibility of executing the intervention under restricted access and adverse environmental conditions. In practice, the selection of a repair strategy depends on whether the damaged zone can be treated fully underwater, under a locally dry environment, or under partially dry conditions; whether the repair materials are compatible with the existing substrate; whether active seepage can be arrested before strengthening; and whether the adopted method can be executed reliably under hydraulic and geometric constraints [(Lu et al., 2022; Rong et al., 2023; Wang et al., 2025)]. For structures affected by continuous leakage, this sequence is especially critical, because strengthening measures cannot achieve the intended structural effect if water continues to propagate through cracks, joints, or weakened interfaces. In such cases, leakage control is not merely a repair operation but a prerequisite for any subsequent strengthening stage.

The present study examines the rehabilitation of the reinforced-concrete intake tower at Lake Batllava, a critical water-supply structure serving the Prishtina region. The tower exhibited a coupled deterioration pattern involving active water leakage at depth, visible cracking, and measurable deviation from verticality within a critical circumferential zone. Such a condition required an intervention strategy capable of addressing both watertightness and structural integrity under severe access constraints imposed by the underwater environment. The study therefore focuses on the deterioration scenario, the engineering rationale of the adopted repair sequence, and the use of polyurethane injection and self-compacting concrete (SCC) ring strengthening as a combined rehabilitation solution.

The case is particularly relevant because the observed damage was not limited to isolated cracking or surface deterioration. Instead, the structure exhibited a coupled deterioration pattern involving measurable deviation from verticality, active water leakage at depth, and distress concentrated in a critical circumferential zone. Such a condition required an intervention strategy capable of addressing both serviceability and structural integrity under conditions where direct access to the damaged area was inherently constrained by the underwater environment. Consequently, the rehabilitation concept had to combine damage arrest, local control of seepage pressure, crack sealing, and structural confinement in a compatible and executable sequence.

Accordingly, the main objective of this paper is to present a scientifically structured reconstruction of the Batllava intervention, with emphasis on three aspects:

(1) the identification of the deterioration scenario and its likely mechanical origin;

(2) the justification of the adopted repair sequence, particularly the need to seal active leakage before strengthening; and

(3) the technical rationale for the use of polyurethane injection and self-compacting concrete (SCC) confinement rings as a combined rehabilitation solution.

The novelty of the paper lies in the integrated interpretation of a real intervention in which leakage sealing and structural strengthening were not treated as independent repair tasks, but as interdependent stages of a single rehabilitation strategy. Rather than presenting underwater repair only as a materials problem, the study highlights the importance of intervention sequencing, constructability under deep-water conditions, and compatibility between hydraulic, structural, and execution requirements. Its contribution is therefore both practical and methodological: it documents how localized pressure reduction, polyurethane-based crack sealing, and SCC ring strengthening were combined to restore serviceability and improve structural stability in a deep-water intake tower subjected to cold-climate exposure.

From a broader perspective, the study also contributes to the documentation of rehabilitation practice for aging hydraulic infrastructure in regions where strategic water-supply structures may remain in long-term service under exposure conditions that were not fully anticipated at the time of original construction. By converting an archived engineering intervention into a structured scientific case study, the paper provides a useful reference for engineers and researchers dealing with similar problems of underwater leakage, localized stiffness degradation, and constructability-driven repair design in reinforced-concrete hydraulic structures.

2. STRUCTURE, CONDITION ASSESSMENT, AND DETERIORATION SCENARIO

The Lake Batllava tower is a reinforced-concrete intake structure located within the reservoir system and used

to collect water at different operational levels for conveyance to treatment and distribution facilities. The structure is approximately 40 m deep, has an internal diameter of 3.50 m, and wall thickness of 0.30 m. Because of its strategic role in regional water supply, rapid but technically reliable intervention became essential once significant leakage was detected.

Field inspection identified concentrated water leakage approximately 22 m below the then-current water level over about three-quarters of the tower circumference (IBMS – Institute of Building Materials and Structures, 2006). The same zone showed visible cracking, with crack widths reaching approximately 1 cm in part of the damaged belt, while geodetic measurements confirmed deviation of the structure from the vertical axis. Acoustic observations during operation further indicated active seepage in the lower part of the tower, consistent with crack-related leakage paths.

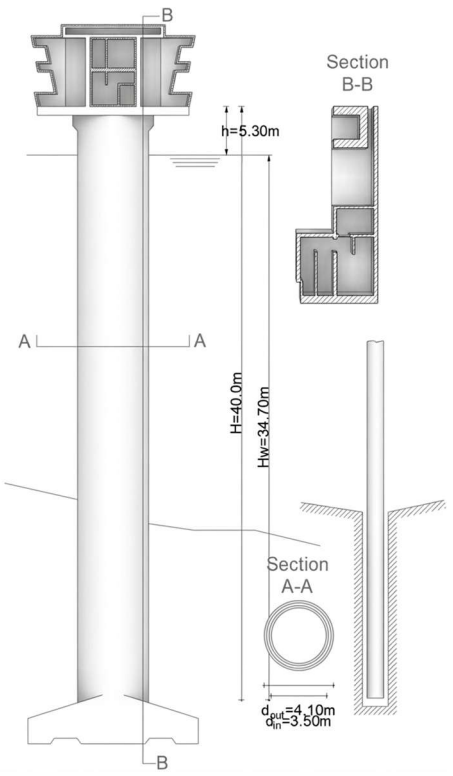
As shown in Figure 1, the distress was concentrated within a critical circumferential zone characterized by active leakage and visible cracking. This condition indicates that the deterioration affected not only local watertightness, but also the structural response of the tower in the damaged belt.

The observed distress was concentrated within a critical circumferential zone characterized by active leakage and visible cracking. This pattern indicates that the deterioration affected not only local impermeability, but also the structural response of the tower in the damaged belt. Once the cracked belt began to leak, the structure faced a combined serviceability and durability problem that required immediate intervention.

3. ACTIONS CONSIDERED AND DETERIORATION MECHANISM

The observed damage was associated primarily with winter icing acting at the waterline in combination with the severe hydraulic exposure of the structure. The recorded ice thickness was approximately 0.60 m, and the resulting horizontal action was considered the principal trigger of cracking and out-of-plumb deformation. In addition to ice action, the engineering assessment considered hydrostatic pressure, wave action, sediment/alluvium effects, and inertial actions as relevant environmental and structural demands acting on the tower.

For interpretation of the deterioration mechanism, the loading framework may be expressed in simplified engineering form. Hydrostatic pressure on the tower wall follows the conventional linear distribution, whereas structural inertia may be represented in pseudo-static form. Ice action may be treated as a screening line load applied at the waterline, consistent with guideline ranges adopted for hydraulic structures



(a)



(b)

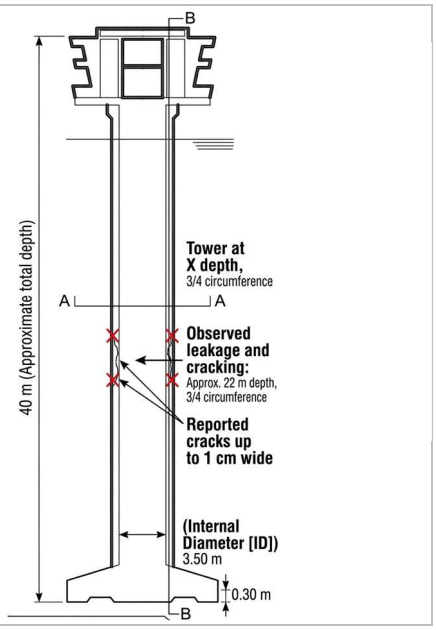


(c)

Figure 1. Geometry and observed distress of the Lake Batllava intake tower: (a) longitudinal elevation of the tower; (b) localized leakage/crack zone in the damaged belt; and (c) internal view of active seepage distributed along the affected circumference.

Table 1. Principal factual characteristics of the structure and recorded damage.

Parameter	Recorded/project value
Structure type	Reinforced-concrete deep-water intake tower
Functional role	Water intake for regional drinking-water supply
Approximate depth	40 m
Internal diameter	3.50 m
Wall thickness	0.30 m
Observed leakage depth	About 22 m below the then-current water level
Extent of leakage	Approximately 3/4 of the circumference
Observed cracking	Cracks reported up to about 1 cm in part of damaged zone
Measured geometry change	Deviation from vertical axis confirmed by survey
Primary interpreted trigger	Winter ice action, with other hydraulic/environmental actions considered in preliminary assessment



in cold regions. These actions are sufficient to explain the physical plausibility of cracking, stiffness reduction, and subsequent leakage development in the damaged circumferential belt [(Alberta Transportation, 2004; Federal Energy Regulatory Commission, 2016; Hellgren et al., 2022; U.S. Army Corps of Engineers, 2005)].

$$p(z) = \gamma_w z \quad (1)$$

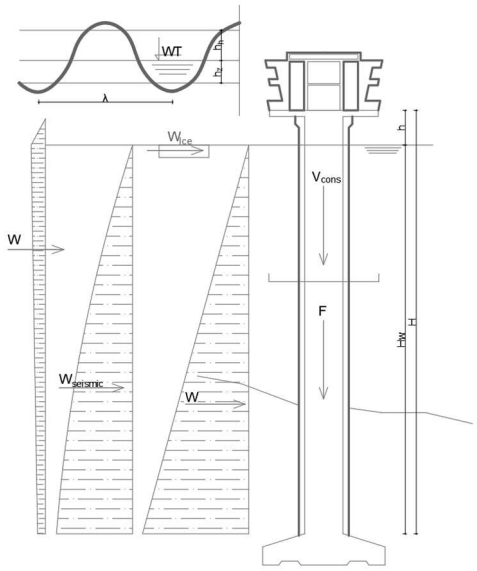
$$Ph = 1/2\ \gamma w\ H^2\ b \quad (2)$$

$$F_{ice} = q_{ice\ bc} \quad with\ 50 \le q_{ice} \le 250\ kN/m \quad (3)$$

$$Fs = k_h W \quad (4)$$

$$Pe = C_w\ k_h\ \gamma_w\ H^2\ b \quad (5)$$

In Eqs. (1)-(5), z is the depth below the free surface, γ_w is the unit weight of water, H is the relevant water depth, b is the tributary width of the structural strip, b_c is the effective ice-contact length at the waterline, q_{ice} is the adopted ice line load, k_h is the horizontal seismic coefficient, W is the self-weight of the structural component considered, and C_w is the hydrodynamic



(a)



(b)

Figure 2. (a) Schematic summary of the environmental and structural actions considered in the engineering assessment, including hydrostatic, ice, wave, sediment/aluvium, and inertial effects and (b) Idealized horizontal action of lake ice on the intake tower at the waterline, as considered in the engineering assessment.

Table 2. Repair materials adopted for leakage control and crack injection.

Material	Type	Primary function
Lamposilex	Rapid-setting cement-based water-stopping material	Immediate seepage control and stabilization around injection points
Resfoam 1KM	Polyurethane-based injection material	Sealing of active leakage paths through water-reactive foam formation

coefficient associated with the adopted simplified reservoir-structure idealization (Figure 2). These expressions are used here as screening-level support for the deterioration mechanism and for the strengthening rationale; they are not presented as a substitute for a full modern design verification.

From a structural point of view, the deterioration scenario can be interpreted as the interaction of environmental demand, local cracking, and progressive loss of watertightness. Once seepage developed through the cracked belt, the damaged zone became vulnerable to continued hydraulic deterioration and stiffness reduction, making section enhancement and confinement necessary in addition to leakage sealing.

The deterioration mechanism may therefore be interpreted as a sequential process in which ice-induced and hydraulic actions initiated localized cracking in the circumferential belt, after which loss of watertightness accelerated the serviceability and durability problems of the structure. Under such conditions, repair limited only to crack closure would have been insufficient, because the damaged zone also required local stiffness enhancement and improved confinement.

4. REHABILITATION METHODOLOGY

4.1 Leakage control and crack sealing

The rehabilitation strategy followed a staged sequence. First, active leakage had to be brought under control. Second, the damaged belt had to be repaired and sealed. Third, the local structural capacity and stiffness of the tower had to be enhanced so that the repaired zone would not remain the weak link under future service conditions. This sequence is consistent with the general principles reported for underwater or difficult-access concrete repair [(Rong et al., 2023; The European Project Group, 2005; Wang et al., 2025)].

Because the damaged zone was underwater and subject to continued seepage, the works were organized to create a partially dry local environment by reducing water pressure at the critical area through external jacketing around the tower perimeter with diver-assisted operations. This did not create ideal dry conditions, but it reduced the hydraulic disturbance sufficiently to permit direct crack preparation, installation of injection ports, and controlled placement of repair materials.

Crack treatment began with localized removal of damaged concrete and controlled opening of the active

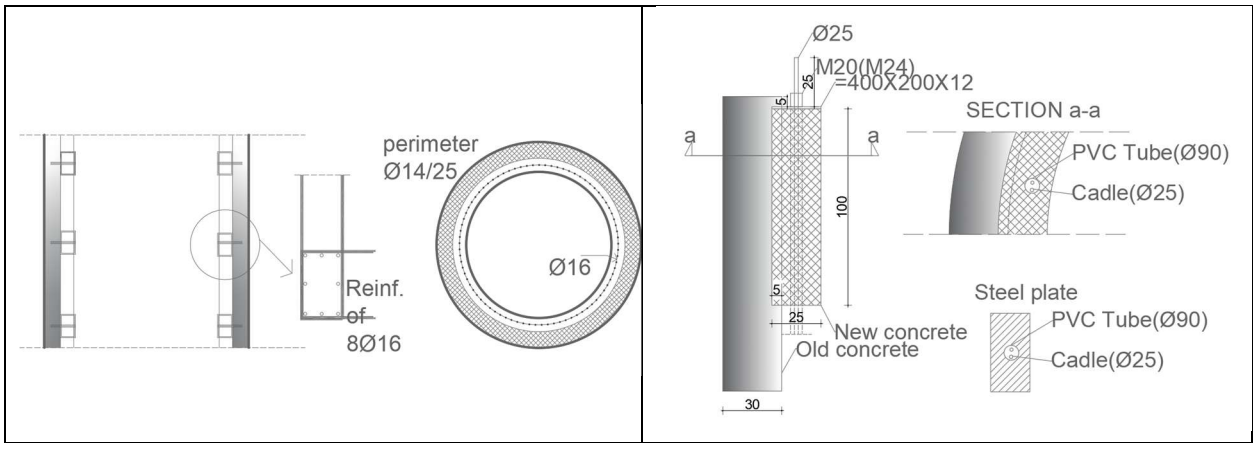


Figure 3. (a) Critical reinforced-concrete ring used for local strengthening of the damaged belt zone and (b) Construction details of the upper ring and compatibility/prestressing arrangement adopted to improve force transfer and global interaction with the critical ring.

Table 3. Trial SCC mixtures developed for the intervention.

Mix	Cement (kg)	Filler (kg)	0/4 aggregate (kg)	4/8 aggregate (kg)	8/16 aggregate (kg)	Water (L)	SP (%)	VMA (%)	fck (MPa)
1	340	50	1050	290	400	190	1.0	0.40	48.50
2	360	40	1250	310	320	195	1.3	0.42	46.32
3	380	30	1100	300	330	200	1.2	0.45	49.55

Note: SP = superplasticizer; VMA = viscosity-modifying admixture.

Table 4. Fresh-property results of the SCC trial mixtures

Mix	Slump (mm)	Flow (mm)	V-Funnel TV,A (s)	V-Funnel TV,B (s)	J-Ring SFJ (mm)	J-Ring ΔhJ (mm)	L-Box Tl,20 (s)	L-Box Tl,40 (s)
1	260	680	8.20	15.0	650	12	0.50	1.10
2	255	630	6.55	10.5	620	15	0.75	1.30
3	265	650	7.10	8.30	640	12	0.85	1.40

leakage paths in a V-shaped profile to a depth of approximately 10 cm. This operation improved access to the crack planes and allowed seepage to be channeled toward controlled treatment points. Immediate water control was achieved using a rapid-setting cement-based water-stopping material, after which polyurethane injection was used to seal the active leakage paths.

4.2 Structural strengthening concept

After leakage control had been achieved, the intervention progressed to structural strengthening. The strengthening concept comprised new reinforced-concrete rings connected to the existing tower, including a ring at the critical damaged belt and an upper ring intended to improve compatibility and force transfer within the repaired system. The role of these elements was not merely geometric enlargement; they were intended to improve local stiffness, enhance confinement, and provide more reliable redistribution of forces through the damaged zone.

The surviving technical data record the principal parameters of the critical strengthening ring: length 4.0 m, thickness 0.25 m, and concrete class C35/45. Anchors and interface-preparation measures were specified to promote composite action between the new ring and the existing structure. Steel cables were also used in association with the upper ring to improve interaction and stabilize the repaired configuration.

5. SCC DEVELOPMENT AND PLACEMENT STRATEGY

Once the leakage paths had been sealed and the strengthening concept had been defined, the critical remaining issue was the selection of a concrete capable of being placed reliably under the geometric and access constraints of the intervention. For this reason, SCC was developed not only as a material solution, but as an execution-oriented component of the rehabilitation strategy.

5.1 Rationale for SCC selection

SCC was selected because the strengthening system had to be cast in a difficult-access environment where reliable vibration of conventional concrete would have been impractical and where segregation resistance during pumping and placement was critical. In such conditions, the fresh concrete must be able to fill confined spaces, pass around reinforcement and anchorage details, and remain stable during pumping and placement [2], [11], [12], [13], [4], [10], [14].

5.2 Mixture development and fresh-state properties

Three SCC trial mixtures were developed using local constituent materials and MAPEI admixtures. Their proportions are summarized in Table 3, while the corresponding fresh-property results are reported in Table 4. The measured parameters include slump/flow, V-funnel, J-ring, and L-box indicators, which collectively provide evidence of flowability, resistance to blockage, and segregation control. These properties directly govern the suitability of SCC for confined rehabilitation works [(Concrete – Specification, Performance, Production and Conformity, 2021; Testing Fresh Concrete – Part 8: Self-Compacting Concrete – Slump-Flow Test, 2019; Testing Fresh Concrete – Part 9: Self-Compacting Concrete – V-Funnel Test, 2010; Testing Fresh Concrete – Part 10: Self-Compacting Concrete – L Box Test, 2010)].

The recorded results show that the trial mixtures achieved fresh-state behaviour consistent with self-compacting placement. The test program therefore supported the use of SCC as part of the structural solution, rather than as a generic material substitution.

5.3 Placement strategy

The pumping and placement arrangement was designed to suit the access constraints of the intervention. Site control was directed toward continuity of placement, avoidance of blockages, and observation of possible instability during pumping. This was particularly important because pumping can alter the rheology of SCC and affect its viscosity, yield stress, and segregation resistance [5,6].

6. DISCUSSION

The Batllava case demonstrates that the success of rehabilitation depended primarily on the sequencing of operations. If the strengthening rings had been cast before active leakage was arrested, the repaired zone would likely have remained vulnerable to persistent seepage, interface deterioration, and incomplete bond development. The adopted sequence first stabilized the hydraulic condition and only then upgraded the structural response.

A second key lesson concerns the choice of SCC. In this case, SCC was justified by the confined geometry, difficult pumping conditions, and the need for reliable filling around reinforcement and the existing substrate. The preserved fresh-property results support this choice and show that constructability was treated as part of the engineering solution rather than as a purely logistical issue.

The ring system addressed the localized nature of the damage while improving compatibility through the upper ring and cable arrangement. In engineering terms, the intervention did not merely seal leakage; it rebuilt the damaged belt into a stiffer and more confined structural zone capable of improved service performance.

Although the case provides a clear engineering basis for the adopted intervention, the available design data do not include a fully preserved modern verification package for all environmental actions and final detailing decisions; the paper therefore focuses on the technically demonstrable aspects of the rehabilitation strategy and its execution.

7. CONCLUSIONS

- The rehabilitation of the Lake Batllava intake tower demonstrates the importance of coupling leakage control and structural strengthening in the repair of underwater hydraulic concrete structures. The tower exhibited severe leakage approximately 22 m below the water level over about three-quarters of its circumference, accompanied by visible cracking and measurable deviation from verticality in the same zone.
- The deterioration was associated primarily with winter ice action acting in combination with severe Hydraulic exposure conditions.
- The adopted intervention combined local pressure reduction, crack preparation and immediate seepage control, polyurethane injection for sealing active leakage paths, and reinforced SCC ring strengthening to restore local stiffness and improve confinement. The case also shows that SCC was not selected as a generic material substitution, but because its filling ability, passing ability, and resistance to segregation matched the execution constraints of the intervention.
- Overall, the study confirms that successful rehabilitation of deep-water intake structures depends not only on material performance, but also on correct sequencing of operations, compatibility between sealing and strengthening measures, and constructability-oriented design.

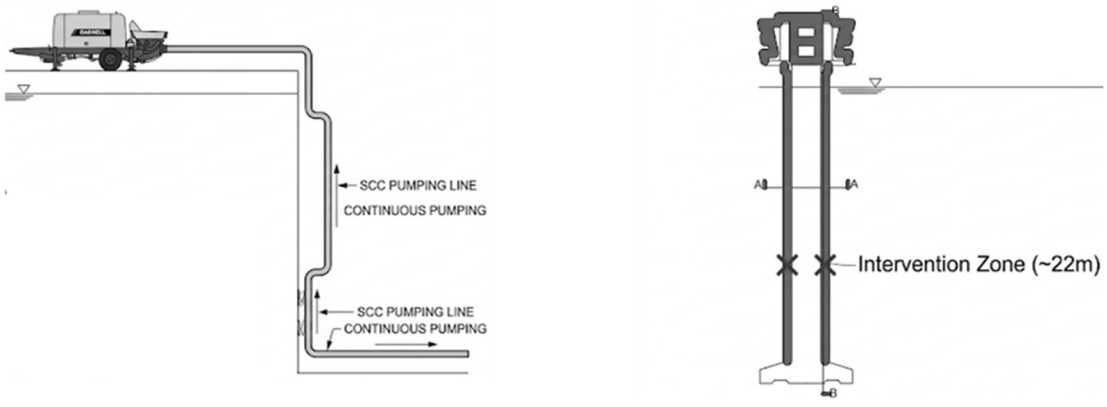


Figure 6. Pumping and casting arrangement used for SCC placement during execution.

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33. SLOVENSKI KOLOKVIJ O BETONIH

Uporaba SCC za izdelavo vidnih betonov

Using SCC to make architectural concrete

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Povzetek

Prispevek obravnava uporabo samozgoščevalnega betona (SCC) za vidne oziroma arhitekturne betonske površine. Poudarek je na reološkem ravnotežju med mejo tečenja, plastično viskoznostjo, tiksotropijo in stabilnostjo zračnih por, saj razlez sam ne zagotavlja kakovostne površine. Predstavljeni so preskusi svežega SCC ter vplivi filerja, kamnolomskih frakcij, pakirne gostote, GGBS (Ground Granulated Blast-furnace Slag; prevod: mleta granulirana plavžna žlindra), mikrosilike in kemičnih dodatkov. Posebej so poudarjeni proizvodnja, transport, opaž, ločevalno sredstvo, način vgrajevanja in omejevanje vodoravnega toka. Sklep je, da moramo pri vidnem SCC projektirati in nadzorovati celoten proces, ne le recepturo betona.

Abstract

The paper discusses the use of self-compacting concrete (SCC) for fair-faced and architectural concrete surfaces. It focuses on the rheological balance between yield stress, plastic viscosity, thixotropy and the stability of the air-void system, since slump-flow alone does not ensure surface quality. Fresh SCC tests are presented together with the effects of filler, crushed aggregate fractions, packing density, GGBS (Ground Granulated Blast-furnace Slag), silica fume and chemical admixtures. Special attention is given to production, transport, formwork, release agents, placing method and limiting horizontal flow. The main conclusion is that fair-faced SCC requires the design and control of the complete concreting process, not only the concrete mix.

Ključne besede: samozgoščevalni beton (SCC), vidni beton, arhitekturni beton, reologija, pakirna gostota, filer, kamnolomske frakcije, mleta granulirana plavžna žlindra (GGBS), mikrosilika, dodatek za uravnavanje viskoznosti (VMA), stabilizator, aerant, antipenilec, način vgrajevanja

Keywords: concrete, crystalline admixtures, fly ash, durability, water permeability, compressive strength, life cycle assessment, susself-compacting concrete (SCC), fair-faced concrete, architectural concrete, rheology, packing density, filler, crushed aggregate, GGBS, silica fume, viscosity modifying admixture (VMA), stabilizer, air-entraining admixture, defoamer, placing method

1. UVOD

Samozgoščevalni beton (SCC – self-compacting concrete) je v literaturi pogosto opisan kot »najbolj revolucionaren razvoj v betonski gradnji v zadnjih desetletjih«. Tehnologijo SCC betona so najprej razvili na Japonskem. Njen razvoj pa je omogočil šele razvoj superplastifikatorjev na bazi polikarboksilatnega etra (PCE). Prvotno so SCC beton razvili kot odgovor na vse večje pomanjkanje usposobljene delovne sile, kasneje pa se je izkazal za ekonomsko koristnega zaradi številnih dejavnikov. SCC se je nato uveljavil tudi po Evropi, tako pri betonih vgrajenih na gradbišču, kot pri prefabriciranih betonskih izdelkih. Praktično uporabnost SCC betona so omogočile tudi številne novo razvite metode merjenja lastnosti svežega SCC.

Vidni oziroma arhitekturni SCC je material, pri katerem betonska površina ni le nosilna konstrukcija, ampak končni estetski izdelek. Pri takem betonu je kakovost površine neposredno odvisna od sestave betona, opažne površine, ločevalnega sredstva, sposobnosti samozgoščevanja, temperature, časa vgrajevanja, nege in razopaževanja.

Klasično zgoščevan oziroma vibriran beton lahko doseže zelo kakovostno površino, vendar zahteva usposobljene delavce in pravilno, enakomerno in zadostno izvedeno zgoščevanje oziroma vibriranje. Nezadostno zgoščevanje / vibriranje ima za posledico

Preglednica 1: Osnovne zahteve SCC in njihov pomen pri vidnem betonu.

Zahteva	Pomen pri SCC betonu	Pomen pri vidnem betonu
Sposobnost zapolnjevanja	Beton mora zapolniti opaž pod lastno težo.	Boljše zapolnjevanje robov, kotov/vogalov in tekstur opaža.
Sposobnost prehajanja	Beton mora preiti skozi armaturo brez blokiranja agregata.	Manj gnezd in manj vidnih napak v gosto armiranih prerezih.
Odpornost proti segregaciji	Matrika mora ohraniti homogenost med transportom in vgradnjo.	Manj lis, pasov vgradnje, izločanja vode, krvavenja in neenotnega videza.
Stabilnost zračnih por	Vsebnost zraka ne sme biti prekomerna, ne sme biti velikih zračnih por / mehurčkov.	Manj por neodzračenosti oziroma površinskih luknjic.
Časovna stabilnost	Lastnosti morajo ostati v ciljnem območju do vgradnje.	Enakomernejši videz med šaržami in manj hladnih stikov.

gnezda, večje zračne votline in slab stik z opažem. Pretirano zgoščevanje / vibriranje pa lahko povzroči segregacijo, izločanje paste, robne napake in neenotno barvo površine.

SCC so razvili prav za situacije, kjer je ročno ali mehansko zgoščevanje težavno, tvegano ali nezaželeno. SCC mora teči pod lastno težo, zapolniti opaž, nemoteno prehajati skozi armaturo in jo oblivati, ter mora pri vsem tem ostati homogen. Zato mora SCC izpolnjevati tri osnovne zahteve: sposobnost zapolnjevanja, sposobnost prehajanja skozi ovire in odpornost proti segregaciji [1].

Pri vidnem oziroma arhitekturnem betonu pa moramo definicijo SCC betona razširiti. Ni dovolj, da beton izpolni merila razleza, L-boxa ali V-lijaka. Površina mora biti enakomerna, brez prekomernih površinskih luknjic, brez lis, sledi krvavenja, brez segregacij, brez izrazitih pasov in sledi toka betona ter brez hladnih stikov. Zato moramo za vidni SCC hkrati projektirati konstrukcijsko obnašanje, reologijo svežega betona, tehnologijo vgradnje SCC, opaže in kakovost stika beton-opaž.

V praksi se pogosto pojavi napačna poenostavitev, da je najboljši SCC tisti z največjim razlezom. Pregled literature kaže nasprotno. Zelo tekoč SCC lahko hitro preide v nestabilnost: prekomerno segregira ali krvavi. Cilj pri vidnem SCC ni maksimalen razlez, ampak stabilna samozgoščevalnost. To pomeni optimalno kombinacijo nizke meje tečenja, dovolj visoke plastične viskoznosti, primerne tiksotropije in kontroliranega sistema zračnih por.

2 SCC ZA VIDNE BETONSKE POVRŠINE

SCC ima za izvedbo vidnih betonov več očitnih prednosti. Ker ni potrebno zgoščevanje / vibriranje, se zmanjša tveganje za prekomerno ali nezadostno zgoščevanje. SCC lahko bolje zapolni robove, kote, teksturirane opažne površine, goste armaturne prereze in zahtevne geometrijske oblike. Hkrati je vgrajevanje tišje, hitrejše in manj odvisno od spretnosti delavcev pri zgoščevanju betona oziroma vibriranju. Po drugi strani je SCC občutljivejši od običajnega betona. Relativno majhna sprememba efektivne vode, vlage v pesku, deleža finih delcev ali doze superplastifikatorja na bazi polikarboksilatnega etra (PCE) lahko povzroči veliko spremembo v obnašanju, od počasnega, lepljivega betona, do pretekoče in segregirane mešanice. Pri vidni betonski površini se te spremembe hitro pokažejo kot nepravilnosti, na primer povečan obseg zračnih luknjic, razne lise, pasovi različnih tonov, robne napake in razlike med posameznimi betoniranimi segmenti / kampadami. V preglednici 1 so podane osnovne zahteve za SCC in njihov pomen pri vidnem betonu.

SCC za vidni/arhitekturni beton moramo obravnavati ne le kot recepturo, ampak kot sistem, ki vključuje: izbor cementa in mineralnih dodatkov; praškasti del (filer);



Slika 1: Primer uporabe teksturiranega opaža – hotel Praška, Zagreb.

Preglednica 2: Preskusi svežega SCC, ki so pomembni pri vidnih oziroma arhitekturnih betonih

Preskus	Standardni okvir	Kaj pove	Komentar za vidni SCC
Razlez s posedom + čas T500	EN 12350-8	Pretočnost in hitrost razlivanja.	Osnovni preskus; nujna tudi vizualna ocena segregacije.
V-lijak	EN 12350-9	Viskoznost in sposobnost pretoka skozi zožitev.	Prekratek čas lahko pomeni nestabilnost; predolg čas lepljivost.
V-lijak po 5 min	EN 12350-9	Če se čas pretoka poveča za več kot 3s v primerjavi s takojšnjo meritvijo.	Potencialna dinamična segregacija betona ali hitra izguba obdelavnosti.
L-box	EN 12350-10	Sposobnost prehajanja skozi armaturne ovire.	Pomemben za stene, stebre in gosto armirane prereze.
Segregacija na situ	EN 12350-11	Odpornost proti segregaciji na preskusu s sitom.	Ključno za enakomerno barvo, teksturo in površino brez segregacijskih mest.
J-ring	EN 12350-12	Prehodnost in blokiranje ob ovirah.	Razlika med razlezom in J-ring razlezom je uporabna za detajle.

agregatni skelet oziroma izbor agregatnih frakcij; kemijske dodatke (superplastifikator na bazi polikarboksilatnega etra (PCE), regulator viskoznosti (VMA - viscosity modifying admixture), zavlačevalec vezanja, aerant ali antipenilec), ki morajo biti medsebojno kompatibilni in kompatibilni s cementom, mineralnimi dodatki in praškastim delom sestave; način mešanja; transport; čas od zamešanja do vgradnje; opaže in vrsto opažne površine; ločevalno sredstvo; temperaturo; hitrost vgradnje betona in predvsem način vgradnje (polnjenje na dnu opaža skozi opažni priključek, kontraktorsko ali klasično polnjenje z vrha) ter nego betona.

Če kateri koli od teh elementov ni obvladovan, lahko še tako laboratorijsko odlična receptura SCC odpove na gradbišču in v takem primeru bo videz vidne površine vprašljiv.

3 PRESKUSI SVEŽEGA SCC IN REOLOŠKA RAZLAGA REZULTATOV

3.1 Preskusi svežega SCC

Preskusi svežega SCC morajo zajeti več lastnosti hkrati. Razlez s posedom pove, ali beton teče, ne pove pa dovolj o prehodnosti skozi armaturo, segregaciji ali površinski kakovosti. Zato se za SCC uporabljajo kombinacije preskusov, ki so v evropski praksi povezane s serijo standardov EN 12350-8 do EN 12350-12 (preglednica 2), ki zajemajo nabor metod za lastnosti svežega samozgoščevalnega betona: Razlez s posedom, V-lijak, L-box, segregacijo na situ, J-ring [2, 3].

Pri SCC je koristno ločiti med empiričnimi preskusi in reološkimi lastnostmi.

- Empirični preskusi so razlez s posedom, čas T500, V-lijak, J-ring, L-box in segregacija na situ.
- Reološke lastnosti pa so meja tečenja, plastična viskoznost in tiksotropija.

Prvi so primerni za rutinsko kontrolo SCC na betonarni in gradbišču, drugi pa omogočajo razlago, zakaj se dve mešanici z enakim razlezom lahko obnašata popolnoma drugače pri črpanju, prehajanju skozi gosto armiran prerez, polnjenju opaža ali pri tveganju za segregacijo. Povezava reoloških parametrov s preskusi na svežem SCC je podana v preglednici 4. Reološke lastnosti SCC so podane v nadaljevanju.

3.2 Preskusi stabilnosti svežega SCC

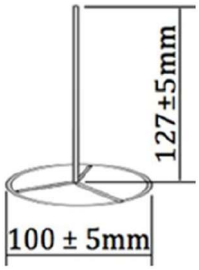
Predvsem iz ameriške literature in prakse je zanimivih nekaj preskusov, ki obravnavajo stabilnost SCC sestav, segregacijo in krvavenje.

HVSI metoda (HVSI – Hardened Visual Stability Index / indeks vizualne stabilnosti strjenega vzorca) obravnava določanje statične segregacije oziroma stabilnosti SCC na strjenih cilindričnih vzorcih. Metoda se navezuje predvsem na: AASHTO R 81 – Standard Practice for Static Segregation of Hardened Self-Consolidating Concrete (SCC) Cylinders; AASHTO – American Association of State Highway and Transportation Officials. HVSI metodo uporabljamo za oceno statične segregacije SCC po strditvi. Sveži SCC vgradimo v standardni valj, po strditvi pa valj vzdolžno prerežemo. Na prerezu vizualno ocenimo porazdelitev grobega agregata po višini in morebitno zgornjo plast paste oziroma malte. Ocena HVSI 0 in 1 pomeni stabilno mešanico, oceni 2 in 3 pa pomenita nestabilno mešanico z vidno segregacijo (preglednica 3). Metoda je potrditvena, saj pokaže dejansko stanje razporeditve agregata po strditvi.

Metoda segregacijskega plovca ni metoda po klasičnem standardu (npr. ASTM ali AASHTO), ampak raziskovalno razvita metoda za hitro oceno statične stabilnosti svežega SCC. Metoda se navezuje na prispevek »SelfConsolidatingConcrete.org / ACBM – Segregation Probe Test«, kjer je opisana metoda in geometrija plovca/sonde.

Metoda segregacijskega plovca je hitra metoda za oceno statične stabilnosti svežega SCC. Sveži SCC vgradimo v valj ali drugo posodo ustrezne višine (lahko se meri kar v posodi laboratorijskega mešalca, če je višina betona v posodi zadostna), pustimo kratek čas mirovati, nato na površino nežno položimo žično tri-kraka sonda oziroma

Preglednica 3: Ocena statične segregacije SCC na vzdolžno prerezanem strjenem valju po kriterijih HVSI in metodi potopitve plovca.

Ocena: HVSI				Globina potopitve plovca
HVSI 0 (stabilen)	HVSI 1 (stabilen)	HVSI 2 (nestabilen)	HVSI 3 (nestabilen)	
stabilen	stabilen	nestabilen	nestabilen	
				 Prikaz meritve metode segregacijskega plovca
Na vrhu prereza ni sloja malte in ni vidne razlike v velikosti ter deležu grobega agregata od vrha do dna vzorca.	Na vrhu prereza ni sloja malte, vendar je opazna rahla razlika v velikosti in deležu grobega agregata od vrha do dna vzorca.	Na vrhu prereza je rahla plast malte, manjša od 25 mm, ter izrazita razlika v velikosti in deležu grobega agregata od vrha do dna vzorca.	Beton je jasno segregiran na vrhu prereza je plast malte večja od 25 mm in/ali po višini vzorca je izrazita razlika v velikosti in deležu grobega agregata.	 Prikaz geometrije plovca / sonde
Ocena: Globina potopitve plovca				
0	1	2	3	
< 4 mm	4 do < 7 mm	7 do 25 mm	> 25 mm	
stabilen	stabilen	nestabilen	močno nestabilen	

plovec. Po določenem času izmerimo globina potopitve. Večja globina potopitve pomeni debelejšo zgornjo plast paste oziroma malte in s tem večjo verjetnost statične segregacije. Metoda zelo dobro sovpada z metodo penetracijskega testa z valjem po standardu ASTM C1712 [17].

Segregacijski plovec in HVSI ocenjujeta isti pojav – statično segregacijo, vendar v različnih fazah. Plovec na svežem betonu hitro zazna, ali se je na vrhu vzorca začela tvoriti plast paste oziroma malte zaradi posedanja grobega agregata. HVSI pa po strditvi pokaže, ali je do takšne segregacije dejansko prišlo. Zato je metoda s plovcem primerna kot hitra napovedna metoda, HVSI pa kot potrditvena metoda. Pri obeh metodah gre za razredno ujemanje in primerljive rezultate (preglednica 3).

Metoda penetracijskega testa z valjem po standardu ASTM C1712 – Standard Test Method for Rapid Assessment of Static Segregation Resistance of SCC Using Penetration Test. Metodo uporabljamo za oceno statične segregacije SCC. Pri tej metodi na površino svežega SCC položimo standardiziran penetracijski valj oziroma penetracijsko telo, nato po določenem času izmerimo globino penetracije. Večja globina penetracije pomeni mehkejšo oziroma bolj s pasto bogato zgornjo plast betona in s tem večjo verjetnost statične segregacije. Metoda se uporablja kot hitra kontrola stabilnosti svežega SCC, vendar rezultat predstavlja napoved segregacije, ne neposredno meritev dejanske porazdelitve grobega agregata po višini vzorca.

Metodo uporabljamo pri razvoju SCC receptur v laboratoriju in tudi za hitro kontrolo pred vgradnjo SCC na terenu.

Metoda statične segregacije z valjem po standardu ASTM C1610 – Standard Test Method for Static Segregation of SCC Using Column Technique. Metodo uporabljamo za oceno statične segregacije SCC. Pri tej metodi sveži SCC vgradimo v vertikalni cilindrični vzorec in pustimo mirovati, da se lahko razvije statična segregacija. Nato ločeno analiziramo zgornji in spodnji del vzorca, pri čemer določimo količino grobega agregata v posameznem delu. Če je v spodnjem delu bistveno več grobega agregata kot v zgornjem, to pomeni, da se je grobi agregat posedel in da je mešanica statično nestabilna. Metoda zato neposredno ocenjuje dejansko ločevanje grobega agregata po višini svežega

betona. Metoda je posebej uporabna pri razvoju SCC receptur, ker pokaže ali je mešanica dovolj kohezivna za visoke/globoke elemente, kot so stene, stebri in drugi visoki opaži. Koheziven SCC je pomemben za vse vrste uporabe, posebej pa pri visokih prerezih, kjer je tveganje statične segregacije večje.

Metodo uporabljamo v laboratoriju in na terenu, vendar na terenu ni nujno dovolj hitra za odločanje tik pred vgradnjo, zato za hitro oceno praviloma uporabljamo ASTM C1712.

Krvavenje SCC po standardu ASTM C232/C232M – Standard Test Method for Bleeding of Concrete. Metodo uporabljamo za določanje relativne količine vode, ki se izloči iz sveže betonske mešanice. Potek preiskave izvedemo tako, da sveži beton vgradimo v posodo predpisanih dimenzij (brez zgoščevanja), površino poravnamo, nato pa vzorec pustimo mirovati. V določenih časovnih intervalih z zgornje površine odvzamemo izločeno vodo, izmerimo njeno količino in izračunamo skupno količino izločene vode oziroma odstotek krvavenja glede na količino vode, ki jo je vzorec vseboval na začetku preskusa. Metoda ne določa splošnih mejnih vrednosti krvavenja, temveč podaja metodo za primerjalno določanje relativne količine vode, ki se izloči iz sveže betonske mešanice.

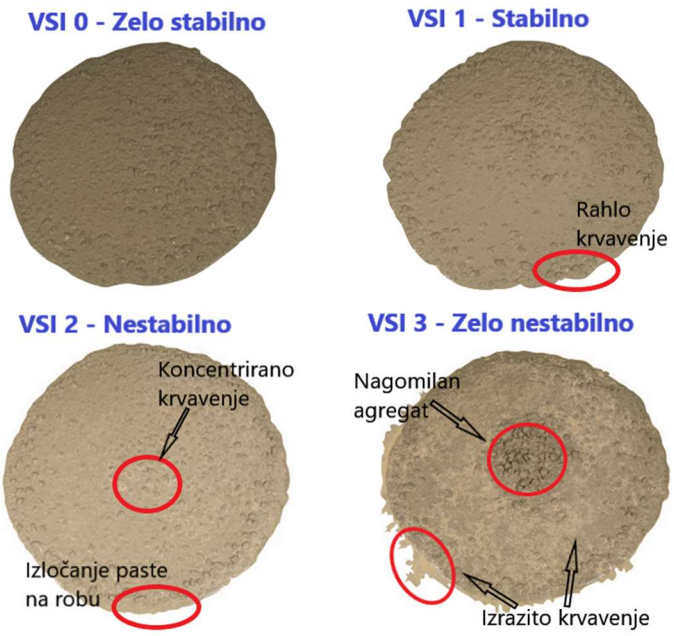
Ta metoda pri SCC pokaže nagnjenost mešanice k izločanju vode. Večja količina izločene vode pomeni večje tveganje. Pri vidnih betonih se to pokaže kot vodne sledi, lise, neenakomerna barva ali šibka površinska plast (prašenje / dusting).

Pri SCC je interpretacija rezultatov odvisna od namena uporabe. Krvavenje SCC je pomemben pokazatelj stabilnosti cementne paste in malte. Čeprav ima SCC zaradi večje količine finih delcev in nižjega vodoprašnega razmerja pogosto manj krvavenja kot običajni beton, lahko pri previsoki količini vode, prenizki viskoznosti ali predoziranju PCE pride do izločanja vode in finih delcev.

Metoda vizualne ocene stabilnosti VSI pri razlezu (VSI – Visual Stability Index) po standardu ASTM C1611 – Standard Test Method for Slump Flow of Self-Consolidating Concrete (Appendix X1). Metodo opisano v dodatku X1 standarda uporabljamo za VSI oceno stabilnosti SCC oziroma odpornosti proti segregacij. Pri vizualni oceni stabilnosti po izvedbi preskusa razleza s posedom pregledamo videz razlitega SCC. Ocenjujemo ali je grobi agregat enakomerno razporejen do roba razleza, ali se na robu pojavi maltni oziroma pastni obroč, ali je prisotno krvavenje ter ali se grobi agregat kopiči v sredini razleza. Ocena VSI 0 pomeni zelo stabilno mešanico brez vidne segregacije, VSI 3 pa izrazito nestabilno mešanico z jasno segregacijo (slika 2).

Metoda VSI je uporabna pri rutinski kontroli SCC in je zelo hitra, vendar je ocena subjektivna in omogoča le vizualno razvrščanje sposobnosti SCC mešanice, da se upira segregaciji oziroma ohrani stabilnost.

Indeks VSI in HVSI sta povezani, vendar nista zamenljivi metodi. VSI je hitra vizualna ocena stabilnosti svežega SCC po razlezu in je primerna za sprotno kontrolo šarž. HVSI je potrditvena metoda na strjenem prerezanem valju, ki pokaže dejansko statično segregacijo po višini vzorca. Mešanice z VSI 0 praviloma dosegajo tudi nizek HVSI, medtem ko VSI 2 ali 3 kaže veliko tveganje za visok HVSI. Pri zahtevnih vidnih ali visokih elementih pa samo VSI ni dovolj, ker lahko mešanica po razlezu izgleda stabilna, kasneje pa zaradi statičnega posedanja agregata pokaže slabši HVSI kar ponavadi vpliva tudi na izgled površine.



Slika 2: Vizualno določeni indeksi VSI po ASTM metod, vir spleti.

3.3 Reološko obnašanje svežega SCC

Reometer je laboratorijska naprava za neposredno določanje reološkega obnašanja svežega betona. Pri meritvi sveži beton obremenjujemo z različnimi strižnimi napetostmi oziroma hitrostmi striženja, naprava pa meri odziv mešanice. Za beton se pogosto uporablja Binghamov model, s katerim obnašanje svežega betona opišemo z dvema osnovnima parametroma: mejo tečenja in plastično viskoznostjo.

Meja tečenja je najmanjša strižna napetost oziroma energija, ki je potrebna, da sveži beton začne teči, lahko si jo predstavljamo kot mejni nagib podlage, po kateri bo beton stekel. *Plastična viskoznost* opisuje odpor betona proti tečenju po tem, ko je beton že začel teči, poenostavljeno pove kako hitro beton teče. Nizka plastična viskoznost pomeni, da SCC hitro teče. Če je meja tečenja previsoka, beton sicer lahko izgleda »koheziven«, vendar ne steče dovolj dobro, slabše zapolni robove in detajle, lahko pride do praznin in slabo oblite armature. Prenizka meja tečenja pa tudi ni vedno dobra.

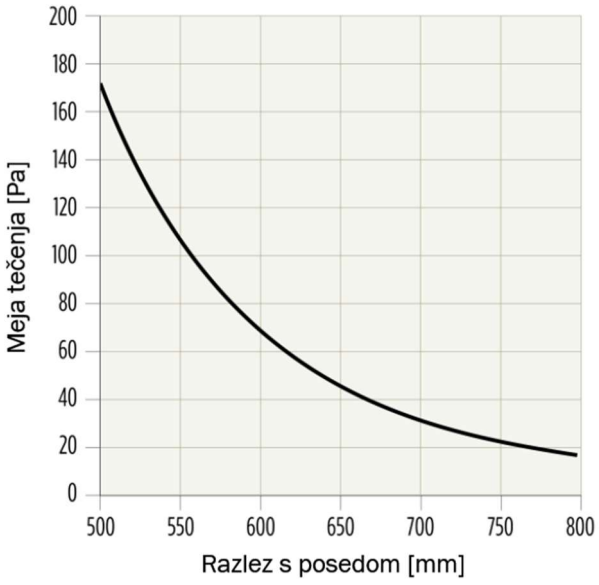
Če viskoznost ni dovolj velika, lahko beton prehitro steče, grobi agregat pa se začne ločevati od malte. Nizka plastična viskoznost pomeni, da SCC hitro teče. To je lahko ugodno za zapolnjevanje opaža in za lepšo površino, vendar se poveča tveganje za segregacijo, krvavenje in ločevanje grobega agregata. Visoka plastična viskoznost pomeni počasnejše tečenje in boljšo stabilnost, vendar lahko beton postane »lepljiv« oziroma »meden«, slabše prehaja skozi armaturo, težje izloča zrak in lahko povzroča več zračnih luknjic na vidni površini. Zato je pri vidnem oziroma arhitekturnem betonu vedno pomembno ravnotežje med mejo tečenja in viskoznostjo. Ključno je, da viskoznost ni niti prenizka niti previsoka. Beton mora imeti dovolj nizko viskoznost za dobro zapolnjevanje in izločanje zraka, hkrati pa dovolj visoko viskoznost za preprečevanje segregacije.

Tiksotropija pomeni, da SCC v mirovanju postopno izgublja fluidnost oziroma želira, pri ponovnem mešanju, črpanju ali dovajanju energije pa del fluidnosti ponovno pridobi.

Tiksotropija je pri SCC zelo pomembna pri stenah, stebrih in visokih opažih. Zmerna tiksotropija je koristna, ker po vgradnji beton hitreje pridobi notranjo stabilnost, zmanjša tveganje segregacije in zmanjša pritisk na opaž. Previsoka tiksotropija pa je lahko neugodna. Če beton med prekinitvami hitro izgubi fluidnost oziroma želira, lahko pride do slabšega spajanja slojev, vidnih linij betoniranja, hladnih stikov, slabše površine in težav pri nadaljevanju vgradnje. To je posebej pomembno pri vidnih betonih, kjer se vsaka prekinitev, sprememba hitrosti vgradnje ali razlika med sloji lahko pokaže na površini.

Za rutinsko projektiranje se pogosto uporabljajo okvirna območja in sicer razlez s posedom približno 650-750 mm, čas T500 približno 2-5 s, V-lijak približno 6-12 s, L-box H2/H1 praviloma najmanj okrog 0,8 ter segregacija v sprejemljivem območju po dogovorjenih merilih. V standardu EN 206 podani meji SR1 < 20 % in SR2 < 15 % sta za vidni beton praviloma previsoki. V primeru, ko beton teče več kot 5 m daleč od mesta vgrajevanja se priporoča stopnja SR < 10%. Te številke so zgolj izhodišče in ne predstavljajo univerzalne rešitve za projektiranje lastnosti SCC. Pri vidnem betonu se lahko zaradi opaža, armature, višine vlivanja in zahtevane površine izbere ožje ciljno območje. Za stene je pogosto bolj varen srednji razred razleza s posedom kot ekstremno visok razred, ki je pogosto nagnjen h krvavenju.

Pri reoloških lastnostih svežega SCC velja, da nizka meja tečenja pomaga pri zapolnjevanju opaža in



Slika 3: Približno razmerje med mejo tečenja in posedom z razlezom, vir [27].

Preglednica 4: Povezava reoloških parametrov s preskusi na svežem SCC

Preskus / lastnost	Najbolj povezan reološki parameter	Praktični pomen pri SCC
Razlez s posedom	Strižna meja tečenja.	Nižja meja tečenja praviloma pomeni večji razlez in lažje začetno tečenje betona.
Čas T500	Plastična viskoznost.	Daljši čas T500 kaže na počasnejše tečenje oziroma večjo viskoznost mešanice.
J-ring	Kombinacija viskoznosti in meje tečenja.	Pokaže, ali beton pri ovirah izgublja tok ali se začenja blokiranje oziroma segregacija.
L-box	Prehodnost in zapolnjevanje.	Poveže sposobnost prehajanja skozi armaturo s sposobnostjo zapolnitve opaža.
Segregacija na situ	Segregacijska stabilnost.	Previsok delež materiala skozi sito kaže na tveganje segregacije; prenizek delež lahko pomeni previsoko viskoznost in slabše zapolnjevanje.
V-lijak V lijak po 5 min	Sposobnost tečenja / zapolnjevanja. Dinamična segregacija	Kratek čas iztekanja kaže dobro tečenje, predolg čas in neenakomeren tok betona pa lahko opozarja na previsoko viskoznost ali blokiranje. Za več kot 3s povečan čas iztekanja po 5 min nakazuje na dinamično segregacijo.

zmanjšuje tveganje za nezapolnjene cone. Vendar sama nizka meja tečenja ni dovolj. Če je plastična viskoznost prenizka, lahko pride do segregacije in krvavenja. Če je viskoznost previsoka, beton postane lepljiv, počasno teče, slabo prehaja skozi ovire in lahko pusti sledi vgradnje kot linije na površini.

V literaturi opisane raziskave reoloških lastnosti [10] so pokazale neposredno povezavo med reološkimi parametri SCC in kakovostjo vidnih površin. Pri mešanicah z mejo tečenja pod 25 Pa so dosežene vrhunske vidne površine, medtem ko so previsoke vrednosti meje tečenja vodile v površinske napake zaradi nezadostnega zapolnjevanja. Pomemben vpliv ima tudi hitrost vezanja sestave, cement, ki deluje počasneje ali zavlačevalec v sestavi, ki lahko povzroča sledi krvavenja na vidni površini tudi, ko je meja tečenja v območju 25 do 50 Pa. Sestave z mejo tečenja višjo od 100 Pa so za vidne betone neprimerne, saj se na površini pojavi preveč napak. Nizka viskoznost vpliva na segregacijo betona. Napake segregacije na površini se pojavljajo pri nizki viskoznosti tudi, če je meja tečenja visoka.

4 VLOGA FILERJA, FINIH DELCEV IN GRANULOMETRIJE AGREGATA

Pri SCC je filer ključni del recepture. Evropske smernice [1] kot praškasti del obravnavajo material pod 0,125 mm, vključno z delom finih delcev v pesku. Pri običajnem betonu se kamnolomski prah pogosto dojema kot nečistoča, pri SCC pa je lahko dragoceno reološko orodje. Vendar samo, če je mineraloško čist, stalne kakovosti, brez prekomerne vsebnosti glin in ustrezne granulometrije.

Filer poveča volumen paste, zapolni praznine med zrni, izboljša kohezivnost in zmanjša nevarnost krvavenja ter segregacije. Pri vidnem betonu lahko pomaga doseči bolj zaprto, enakomerno površino. Po drugi strani prevelika količina filerja ali filer z veliko specifično površino poveča potrebo po vodi ali superplastifikatorju (PCE), poveča viskoznost, zmanjša razlez in lahko povzroči lepljiv SCC s slabšo prehodnostjo.

Pri kamnolomskih agregatnih frakcijah je izziv izdelave sestave SCC večji kot pri rečnih agregatih (preglednici 5 in 6). Rečni agregati so praviloma zaobljen, z nižjim notranjim trenjem, zato SCC lažje teče. Drobljen agregat ima oglata, hrapava in pogosto ploščata zrna, večjo specifično površino in več prahu. To poveča potrebo po pasti, poveča občutljivost na vlago in količino PCE ter lahko poslabša rezultate J-ringa in L-boxa. Vendar drobljen agregat ni slab sam po sebi. Pakirna gostota (packing density) materialov (finega, grobega agregata in filerjev) v SCC je ključna za doseganje visoke fluidnosti in stabilnosti brez segregacije.

Pri SCC težimo k čim večji pakirni gostoti agregata (običajno med 0,65 in 0,70 v nasutem stanju), kar pomeni čim večjo zasedenost prostora oziroma čim manjše praznine (voids) med zrni agregata, ki jih mora zapolniti pasta, kar omogoča boljši izkoristek materiala, manjšo krčenje in boljšo reologijo. Z dobro porazdeljenimi kamnolomskimi frakcijami agregata tako, da dosežemo čim večjo pakirno gostoto zrn, lahko dobimo zelo stabilen SCC, pogosto tudi z visoko tlačno trdnostjo [7]. Največja pakirna gostota ne pomeni vedno samodejno najboljše SCC sestave, ker morata biti zagotovljena tudi sposobnost prehajanja in odpornost proti segregaciji. Doseganje čim večje pakirne gostote agregata ne pomeni vedno, da ima skupna agregatna krivulja lep videz (gladka skupna krivulja in brez lomov).

Poleg dobre razporeditve zrn agregata je pomembno doseči tudi nizko notranje trenje med agregatnimi zrni (tu imajo prednost rečni agregati) in zagotoviti enakomerno sejalno sestavo posameznih frakcij agregata skozi obdobje gradnje. Pri SCC imata vodno/praškasto razmerje in volumen paste pogosto večji vpliv kot samo vodovezivno razmerje [7].

4.1 Opis metode pakirne gostote (packing density)

Metoda packing density pri SCC temelji na eksperimentalnem določanju gostote zlaganja različnih kombinacij agregatnih frakcij. Za tri frakcije uporabljamo trikotni oziroma ternarni diagram, kjer vsak vogal trikotnik predstavlja 100 % ene frakcije,

Preglednica 5: Posebnosti kamnolomskih frakcij pri SCC.

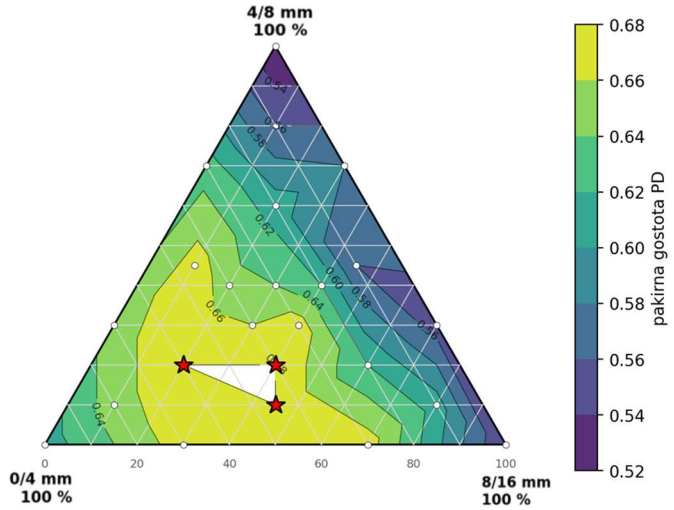
Lastnost kamnolomskega agregata	Učinek na SCC	Možen ukrep
Oglata in hrapava zrna	Več notranjega trenja, manjši razlez, višja potreba po pasti.	Optimizacija frakcij, več fine paste, ustrezen PCE.
Ploščata/podolgovata zrna	Slabše prehajanje, večje tveganja blokiranja.	Omejitev neugodnih oblik, nižji Dmax, več kontrolnih preskusov.
Veliko finih delcev	Večja viskoznost, občutljivost na vodo in PCE.	Ločena kontrola delcev <0,125 mm in <0,063 mm, test MB metilen modro.
Glinasti delci	Adsorpcija PCE, izguba razleza, nestabilna reologija.	Test MB metilen modro, pranje, izbor druge frakcije ali dodatka.
Nihanje vlage 0/4	velika nihanja razleza in segregacije.	Pogosta meritev vlage in korekcija vode.

vsaka notranja točka pa določeno volumensko razmerje treh frakcij. Za vsako izbrano točko pripravimo agregatno mešanico, nasujemo v posodo znanega volumna, stehtamo in iz izmerjene mase ter gostot posameznih frakcij izračunamo absolutni volumen zrn. Pakirna gostota (packing density, PD) je razmerje med absolutnim volumnom zrn in volumnom posode, delež praznin pa je izražen kot 1 – PD (slika 4).

Pri SCC je cilj izbrati agregatno kombinacijo z visoko, vendar praktično uporabno gostoto pakiranja, saj manjši delež praznin zmanjša potrebno količino paste. Pasta mora zapolniti praznine med zrni in zagotoviti dodatni presežek za samozgoščevanje, tečenje in prehajanje skozi armaturo. Zato pakirna gostota ni končni kriterij, temveč izhodišče za optimiziranje recepture SCC, ki jo moramo potrditi še s poskusno mešanico in preskusi svežega SCC.

Uporaba kamnolomskega apnenčevega filerja v sestavi SCC izboljša stabilnost sveže sestave in trajnost strjenega SCC. Vendar se ob večanju deleža filerja praviloma zmanjša razlez ter poveča mejo tečenja in viskoznost [6]. Iz praktičnega vidika je najpomembneje zagotoviti optimalno sestavo. Premalo finih delcev pomeni nevarnost krvavenja, segregacije in grobe površine. Preveč finih delcev pomeni visoko viskoznost, lepljivost, slabšo prehodnost skozi armaturo in večjo občutljivost na PCE. Pri arhitekturnem SCC je treba ločiti tudi med koristnim filerjem in škodljivim prahom. Koristen filer je stabilen po sestavi, brez glinenih primesi, s primerno granulacijo in znanim vplivom na PCE. Škodljiv prah pa je spremenljiv, glinast ali preveč fin ter povzroča nepredvidljivo reologijo ter lahko vpliva tudi na barvo površine.

Za kamnolomski agregat je posebej pomembna frakcija 0/4 oziroma 0/2. Dve frakciji agregata 0/4 imata lahko skoraj enako sejalno krivuljo, a se v SCC obnašata zelo različno zaradi oblike zrn, hrapavosti, deleža delcev pod 0,125 mm, deleža delcev pod 0,063 mm, količine glinenih primesi (meritev MB metilen modro) in mineraloško petrografske analize agregata. Zato pri SCC iz kamnolomskih frakcij priporočamo izvesti predhodne



Slika 4: Primer ternarnega diagrama, zvezdice označujejo tri primere kombinacij frakcij agregata z doseženo največjo pakirno gosto, vir splet.

Preglednica 6: Priporočila za SCC iz kamnolomskih frakcij.

Parameter	Tipično tveganje pri drobljenem agregatu	Priporočilo za vidni SCC
Dmax	Večje zrno poveča tveganje blokiranja in slabega zapolnjevanja.	Za tanke/goste elemente pogosto 8 mm, običajno pa 16 mm.
0/4 frakcija	Največji vpliv na vodo, količino PCE in razlez.	Stalna kontrola vlage, finih delcev in vsebnosti glinenih delcev (test MB metilen modro).
Delež paste	Premalo paste povzroči grobo površino, preveč paste poveča krčenje in višjo ceno SCC.	Optimizacija pakirne gostote agregatnega skeleta in količine praškastih delcev.
Filer	Prevelika količina filerja poveča viskoznost in lepljivost.	Filer uporabiti kot kontroliran sestavni del, ne kot naključen prah.
PCE	Prekomerna doza lahko poveča segregacijo in vsebnost zraka v sestavi.	Izbrati kompatibilen PCE in preveriti časovno stabilnost.

poskusne na malticah in pastah za oceno občutljivosti peska pred izdelavo sestave SCC. (meritve mini razleza s stožcem enakim kot pri preskusu razleza malte po EN 1015-3, za paste razlez z valjčkom ali Marshov lijak enak kot je opisan v EN 445).

5 PRIMERJAVA METOD PROJEKTIRANJA SESTAVE SCC

Prikazana je primerjava več pristopov projektiranja samozgoščevalnega SCC. Prikazane so značilnosti metode Okamura/JSCE, metode Edamatsu-Nishida-Ouchi, švedski CBI pristop ter francoski LCPC pristop z modelom pakiranja. Poudarek je na tem, kako posamezna metoda določa volumen paste, volumen malte ter razmerje med grobimi in drobnimi agregatnimi frakcijami.

Pri običajnem vibriranem betonu se zgoščevanje doseže z dovedeno energijo vibriranja. Pri SCC mora beton zapolniti opaž in prehajati med armaturo in jo obliti pod delovanjem lastne teže. Zato je projektiranje sestave SCC predvsem volumsko in reološko vprašanje, koliko paste je potrebno, da zapolni praznine med agregatnimi zrni, da oblije zrna agregata in omogoči tok betona, hkrati pa ne povzroči segregacije, krvavenja, previsokega krčenja ali previsokih stroškov.

Pri SCC ključno vlogo igra volumska bilanca: 1 m³ = $V_{zrak} + V_{pasta} + V_{fini\ agregat} + V_{grobi\ agregat}$. Pasta je nosilec reologije, malta je nosilec prehajanja skozi ovire, grobi agregat pa najbolj vpliva na blokiranje, notranje trenje in ekonomiko. Pasta je transportni medij za agregat, njen volumen mora biti večji od praznin med agregatnimi zrni.

5.1 Okamura/JSCE oziroma klasični japonski pristop

Izhodišče metode: Najbolj znan zgodnji pristop izhaja iz japonskega razvoja SCC. Beton je obravnavan kot sistem grobega agregata in malte. Da se zmanjša trčenje in zagozdenje grobih zrn, je volumen grobega agregata omejen. Da zagotovimo stabilnost, uporabimo relativno visok delež prahu oziroma paste. V evropskih in EFNARC smernicah je ta logika povzeta kot postopek, ki najprej določi vsebnost zraka, nato grobi agregat, fini agregat, sestavo paste in šele nato razmerje voda/prah ter dozo superplastifikatorja [22].

Določanje grobega agregata: V prvotnem Okamura-Ozawa postopku volumen grobega agregata pogosto nastavimo približno na 50 % prostornine trdne faze betona oziroma na omejen delež, ki preprečuje trčenje zrn. V JSCE pristopu grobi agregat izberemo glede na zahtevnost konstrukcije oziroma samovgradljivostni razred. Pogosto citirani razponi absolutnega volumna grobega agregata so približno 0,28-0,30 m³/m³ za najbolj zahteven razred, 0,30-0,33 m³/m³ za srednji razred in okoli 0,32-0,35 m³/m³ za manj zahtevne elemente [23].

Določanje finega agregata in paste: Fini agregat pri klasičnem postopku določamo kot delež malte, pogosto približno 40 % volumna malte, pri čemer malta vsebuje pasto in pesek. Količino paste določimo posredno, ko sta znana vsebnost zraka in grobi agregat ter izbrano razmerje peska v malti, preostali volumen pripada pasti. Razmerje voda/prah in doza PCE nato določimo s preskusi na malti, na primer mini razlezom in mini V-lijakom. EFNARC kot primer navaja ciljni razlez malte 24-26 cm in čas mini V-lijaka 7-11 s, pri čemer se razmerje voda/prah in PCE prilagajata do doseganja cilja [22].

Prednosti: Metoda je pregledna, varna in robustna, zato je dobra začetna osnova za recepture z neznanimi lokalnimi materiali. Slabosti: Ker je konzervativno, pogosto vodi do večje količine paste in prahu, kot bi bila nujno potrebna pri optimiziranem agregatnem skeletu. Pri kamnolomskih frakcijah je to lahko koristno za stabilnost, vendar poveča viskoznost, krčenje in strošek.

5.2 Metoda Edamatsu, Nishida in Ouchi

Izhodišče metode: Metoda Edamatsu-Nishida-Ouchi je nadgradnja zgodnjega japonskega pristopa. Namesto da bi delež peska v malti vnaprej fiksirali, metoda obravnava interakcijo med grobim agregatom in delci malte. Avtorji so razvili pristop za določanje primernega deleža finega agregata v malti in za določanje volumskega razmerja voda/prah ter doze superplastifikatorja z uporabo preskusov na malti [24].

Določanje količine paste: Pasto ne določimo kot poljubno visok varnostni presežek, temveč preko reologije malte. Najprej preverimo, pri katerem razmerju pesek/malta je malta dovolj tekoča in hkrati dovolj stabilna, da lahko prenaša groba zrna brez blokiranja. S tem neposredno določimo, koliko paste je potrebno v malti. Če je pesek hrapav, drobljen ali slabo granuliran, je za enako interakcijo potrebno več paste ali drugačno razmerje voda/prah in PCE.

Določanje fine frakcije agregata: Fini agregat optimiziramo z maltno fazo, grobi agregat pa preverjamo s samovgradljivostjo betona. Bistvo metode je, da delež finega agregata ni univerzalna konstanta, temveč rezultat preskusov z dejanskim peskom, prahom in dodatki. V literaturi je posebej poudarjena uporaba preskusov razleza in lijaka za malto ter preskusov, ki upoštevajo interakcijo malte z modelnim grobim agregatom [24].

Praktična interpretacija: Ta metoda je uporabna kot srednja pot med konservativnim JSCE pristopom in zahtevnejšimi modelnimi metodami. Zanimiva je, ker omogoča, da pri kamnolomskem pesku ne predpostavimo vnaprej, da je 40 % peska v malti optimalna količina, ampak to določimo z dejansko reologijo malte.

5.3 CBI metoda – švedski pristop

Izhodišče metode: CBI metoda, razvita v švedskem okolju, beton obravnava kot dvofazni sistem, tekoča faza je pasta, trdna faza pa kombinirani agregatni skelet. Cilj je zmanjšati volumen paste z optimiziranjem agregatne faze, vendar ne na račun prehodnosti skozi armaturo. V literaturi je CBI opisan kot pristop, ki združuje kriterij maksimalne medzrnske razdalje in kriterij blokiranja; s prvim določamo razmerje grobi/fini agregat, z drugim pa največji dovoljen volumen agregata za dane razmere v konstrukciji [25].

Določanje agregatnih frakcij: Najprej sestavimo kombinirano granulometrijo agregatov in iščemo razmerje med frakcijami, ki daje ugodno pakiranje in zadostno razdaljo med zrni. Pri tem metoda ne gleda samo na standardno krivuljo, temveč tudi na realne pogoje vgradnje Dmax, obliko zrn, razdaljo med armaturo in širino kritičnih prehodov. Če je razdalja med armaturo majhna ali je agregat oglat, mora biti volumen grobega agregata nižji, razmerje finega agregata in malte pa višje.

Določanje paste: Ko je določen največji dopustni volumen agregatnega skeleta, minimalno pasto določimo kot volumen, potreben za zapolnitev praznin ter za ustvarjanje tekoče faze, ki zagotovi prehodnost. Kasnejši razvoj metode je dodal tudi kriterij tekoče faze, s katerim preverjamo minimalno pasto oziroma mikro malto, potrebno za zadostno prehodnost v L-boxu [25].

Prednosti: CBI je zelo uporaben, kadar želimo zmanjšati prevelik volumen paste in izkoristiti lokalne agregate, vendar še vedno varno obvladovati blokiranje. Slabosti: Zahteva več podatkov o agregatih in bolj disciplinirano laboratorijsko preverjanje. Pri zelo spremenljivem drobljenem pesku je treba stalno kontrolirati prah, vlago in obliko zrn.

5.4 LCPC pristop – stisljivi model pakiranja

Izhodišče metode: Francoski LCPC pristop Sedrana in de Larrarda je najbolj modelno zasnovan med primerjanimi metodami. Temelji na stisljivem modelu pakiranja (Compressible Packing Model, CPM) in orodjih, kot sta BTRHEOM za reološko karakterizacijo in RENÉ-LCPC za optimiziranje granulometrijskega skeleta. Namen metode je hitro priti do teoretično optimizirane sestave z minimalnim potrebnim volumnom paste, ob hkratnem upoštevanju tečenja, blokiranja in segregacije [26].

Določanje agregatnih frakcij: LCPC najprej matematično obravnava pakiranje vseh zrnatih komponent cementa, filerja, peska in grobih frakcij. Vhodni podatki so gostote, granulometrija, oblika/kompaktnost frakcij, absorpcija in pakirna gostota posameznih materialov. Model poišče zrnato kombinacijo z visoko pakirno gostoto, s čimer se zmanjšajo praznine in s tem osnovna potreba po pasti.

Določanje paste: Pasta se določa kot presežek nad prazninami optimiziranega skeleta, vendar ne samo geometrijsko. LCPC pristop poskuša povezati sestavo z napovedjo meje tečenja, plastične viskoznosti, razleza, časa tečenja, sposobnosti polnjenja in segregacijske stabilnosti [26]. Zato je to metoda, kjer količino paste ne določimo s fiksnim odstotkom, ampak z modelom najmanjša količina paste, ki še zagotovi zahtevano reologijo in prehodnost.

Prednosti: LCPC metoda je najboljša pri optimiziranju paste, zmanjšanju stroška in zmanjšanju krčenja, ker skuša izkoristiti pakiranje celotnega zrnavostnega sistema. Slabosti: Zahteva največ podatkov, modelno znanje in validacijo z realnimi preskusi. Za vsakodnevno uporabo v betonarni je lahko zahtevna, vendar je odlična kot razvojna metoda.

5.5 Povzetek metod

Pri projektiranju SCC sestave količine paste ni mogoče določiti samo iz zahtevane trdnosti ali iz vodocementnega razmerja. Pasta je reološki medij, ki mora zapolniti praznine med zrni agregata, obliti vsa zrna, zmanjšati trenje ter zagotoviti prehajanje skozi armaturo. Klasični japonski in JSCE pristop to dosežeta konservativno z omejitvijo grobega agregata in večjim deležem paste. Metoda Edamatsu-Nishida-Ouchi izboljša določanje malte z upoštevanjem interakcije med finim agregatom, pasto in grobimi zrni. CBI in LCPC pristopa pa skušata količino paste racionalno zmanjšati z optimiziranjem agregatnega skeleta in upoštevanjem blokiranja. Pri kamnolomskih frakcijah, ki imajo večje trenje in večjo variabilnost finih delcev, je zato ključno laboratorijsko preverjanje malte in betona, ne samo izračun recepture. Cilj ni minimalna pasta za vsako ceno, temveč najmanjša pasta, ki še daje stabilen, robusten, samozgoščevalen in površinsko kakovosten SCC.

6 MINERALNI DODATKI

6.1 Vpliv granulirane plavžne žlindre (GGBS/GGBFS)

Mineralni dodatek granulirane plavžne žlindre GGBS oziroma GGBFS (ground granulated blast-furnace slag) ima pri SCC več vlog. Lahko je del veziva, lahko del praškastega sistema, v nekaterih raziskavah pa tudi delna zamenjava fine frakcije. V vseh primerih vpliva na pakiranje delcev, kohezivnost, potrebo po PCE, viskoznost, čas vezanja, toploto hidratacije in trajnost. Pri vidnem betonu je še posebej pomemben vpliv na homogenost paste in zmanjšanje krvavenja.

GGBS lahko pri zmernem deležu (10–20 %) zmanjša trenje, izboljša razlez in sposobnost prehajanja (L-box) ter poveča stabilnost [4]. Pri previsokem deležu (30 %) pa se lahko poveča viskoznost in zmanjša sposobnost prehajanja [5]. Pri arhitekturnem SCC to pomeni, da je GGBS koristen predvsem kot del optimiziranja praškastega sistema. Vpliva na bolj gosto in homogeno cementno matriko, zmanjša krvavenja in daje bolj enakomerno vidno površino.

GGBS lahko pozitivno vpliva tudi na trajnost. Zaradi latentno hidravličnega delovanja in izboljšanja mikrostrukture cementne matrice se pogosto izboljša odpornost proti vdorom agresivnih snovi. Pri vidnem betonu je to pomembno, ker je površina neposredno izpostavljena okolju. Uporaba GGBS lahko povzroči počasnejši zgodnji razvoj trdnosti in zato lahko vpliva na razopaževanje, predvsem pri hladnem vremenu ali zahtevnih opažnih površinah je to zelo pomembno.

6.2 Mikrosilika

Mikrosilika je pri SCC učinkovit reološki in trajnostni dodatek, vendar deluje drugače kot GGBS. Zaradi izredne finosti poveča kohezivnost cementne matrice, zmanjša krvavenje in izboljša odpornost proti segregaciji. Zgoščena in stabilna cementna pasta lahko prispeva k bolj homogeni površini ter manjši prepustnosti betona.

Po drugi strani pa mikrosilika poveča občutljivost recepture, saj lahko zaradi velike specifične površine poveča potrebo po superplastifikatorju PCE in plastično viskoznost; posledično se povečata čas T500 in čas V-lijaka, poslabša pa se lahko tudi L-box. Previsok delež mikrosilike ali neustrezna kombinacija s PCE lahko povzroči lepljiv beton, slabše izhajanje zraka, več zračnih luknjic na površini in težave pri zaključni obdelavi. Ker mikrosilika zelo učinkovito zmanjša ali odpravi izcejanje vode, lahko povzroči na površini betona hitrejše tvorjenje filma v obliki skorjice, hladne stike ali površinske napake, če pride do prekinitev pri dobavi oziroma vgrajevanju SCC.

Koristnost mikrosilike pri vidnem SCC je lahko vprašljiva. V primeru uporabe črne ali temno sive mikrosilike pri SCC z velikim razlezom (večjim od 700 mm) se bodo med procesom odzračevanja iz SCC na površino izločali fini delci mikrosilike. Ti delci plavajo na površini, se oprijemajo opažne površine in kasneje na površini betona tvorijo neenakomerne linije (»zebra efekt«). Manj problematična z vidika videza površine je uporaba bele in svetlo sive mikrosilike. Mikrosiliko je potrebno uporabiti v optimalnem deležu, ki mora biti preverjen s preskusi razleza, časa T500, V-lijaka, L-box/J-ring, segregacije ter na poskusnim poljem večjega formata, kjer se oceni videz površine.

7 KEMIJSKI DODATKI

7.1 Regulator viskoznosti (VMA)

Dodatek za uravnavanje viskoznosti oziroma VMA je pri SCC namenjen predvsem povečanju kohezivnosti in odpornosti proti segregaciji. Medtem, ko superplastifikator PCE omogoča velik razlez in znižanje meje tečenja, VMA stabilizira pasto oziroma malto in zmanjša možnost ločevanja grobega agregata, krvavenja ter izločanja paste. Njegova uporaba je posebej koristna pri recepturah z nižjo količino praškastega dela, pri spremenljivi vlažnosti agregata, pri kamnolomskih peskih z nihajočim deležem finih delcev in pri betonih, kjer je zahtevana visoka robustnost svežih lastnosti. Pri vidnem oziroma arhitekturnem SCC lahko VMA prispeva k bolj homogeni površini, manjšemu tveganju segregacijskih lis, manjši nagnjenosti k plastičnemu posedanju in bolj ponovljivemu videzu med šaržami. Vendar mora biti odmerek VMA skrbno optimiziran, previsoka viskoznost lahko povzroči počasno tečenje, slabšo prehodnost skozi armaturo, težje izhajanje zraka in več površinskih luknjic. Zato VMA ni nadomestilo za dobro projektirano zrnavostno sestavo, ustrezen volumen paste in združljiv PCE, ampak dodaten reološki regulator za povečanje stabilnosti in robustnosti SCC.

7.2 Stabilizator

Stabilizator oziroma water retaining admixture deluje predvsem tako, da zadrži prosto vodo v cementni pasti ali malti. To pomeni, da se voda težje loči od trdnih delcev. Posledično se zmanjša krvavenje, zmanjša se možnost vodnih kanalov ob opažu in izboljša se homogenost površine. Pri SCC je to pomembno zato, ker je beton zelo tekoč. Če je viskoznost prenizka ali je vodovezivno oziroma vodoprašno razmerje previsoko, lahko pride do izcejanja vode in finih delcev. Na vidnih površinah se to pokaže kot vertikalne sledi, vodni kanalčki oziroma spiranje, ki so posledica krvavenja vode in finih delcev, povezano s previsokim vodoprašnim razmerjem ali prenizko viskoznostjo, kot možen ukrep je navedena uporaba VMA oziroma povečanje viskoznosti.

V tehničnem smislu stabilizator ni nujno enak VMA, v praksi pa se pogosto zgodi, da ima stabilizator učinek VMA. V praksi lahko stabilizator deluje podobno kot VMA, saj zadrževanje vode poveča kohezivnost in stabilnost sistema. Pri vidnem SCC je uporaba obeh dodatkov koristna predvsem za povečanje homogenosti in ponovljivosti površine, vendar mora biti količina skrbno optimizirana. Previsoka viskoznost lahko poslabša izhajanje zraka, poveča čas T500 oziroma V-lijak in povzroči več površinskih luknjic na vidni površini.

Preglednica 7: Vpliv sprememb sestave SCC na reološke parametre, puščice prikazujejo pričakovano smer spremembe sestave.

SPREMEMBA SESTAVE	MEJA TEČENJA	PLASTIČNA VISKOZNOST
Več paste (manj agregata)	↓	↓
Več superplastifikatorja (PCE)	↓	↓
Več elektrofiltrskega pepela	ostane nespremenjena	↑
Več mikrosilike	ostane nespremenjena	↓
Več VMA	↑	ostane nespremenjena
Višje vodocementno razmerje	ostane nespremenjena	↓
Bolj zaobljena oblika zrn (rečni agregat)	↓	↓
Večja finost finega agregata	↑	↑

7.3 Antipenilec in aerant – kontrola zračnih por

Zračne pore so pri vidnem SCC ena pomembnejših, a pogosto premalo kontroliranih lastnosti. PCE superplastifikatorji lahko povečajo zadrževanje zraka in stabilizirajo večje zračne mehurčke. Takšni mehurčki se zaradi vzgona počasi pomikajo proti vrhu opaža. Ločevalno sredstvo naneseno na opažno ploskev odriva te mehurčke od površine. Odvisno od viskoznosti in delovanja sestave SCC (tiksotropija) se ta proces v nekem trenutku upočasni in kasneje ustavi. Mehurčki v procesu upočasnjenega pomikanja zaradi zgoščevanja, želiranja (večje viskoznosti) svežega SCC večinoma končajo na opažni površini, ker jih vzgon ne more odvleči do vrha elementa. Zrak se v sestavo SCC ne vnaša samo z dodatki. Dosti se ga vnese v sestavo med samim transportom (vrtenje bobna avtomešalca) in vgrajevanjem SCC. Način in hitrost vgrajevanja tu igrata ključno vlogo. Nekaj od ujetega zraka v sestavi SCC se na površini pokaže kot pore neodzračenosti (bugholes) oziroma površinske luknjice. Običajni SCC preskusi, kot so razlez, V-lijak in L-box, ne zadoščajo za oceno sistema zračnih por. Mešanica lahko izpolni samozgoščevalne kriterije, a ima lahko še vedno previsok ali neugodno porazdeljen zrak.

Antipenilec oziroma »anti-foaming admixture« (AFA) je namenjen zmanjševanju neželenega penjenja in večjih zračnih mehurjev. V raziskavah [8] je bilo ugotovljeno, da dodatek AFA v kombinaciji s PCE v svežem SCC zmanjša količino zraka, poveča razlez s posedom in zmanjša viskoznost (čas T500 in V lijak) ter podaljša ohranjanje obdelavnosti svežega SCC. Pri tem je pomembno, da je sestava SCC tako optimizirana, da v primeru tekoče sestave (velik razlez s posedom), dodatek AFA ne povzroči segregacije.

Tudi preiskave na cementni pasti (meritve mini razleza s stožcem enakim kot pri preskusu razleza malte po EN 1015-3 in mini V lijaku) kažejo, da majhne doze antipenilca na osnovi glikolnega etra v prisotnosti PCE lahko povečajo pretočnost, znižajo strižno mejo tečenja, znižajo plastično in navidezno viskoznost ter povečajo gostoto in tlačno trdnost paste [4]. To je za vidni beton pomembno, ker je osnovni cilj zmanjšati površinske luknjice in dobiti kompaktnejši stik z opažem kadar so opaži s teksturo.

Delovanje antipenilca pri vidnem betonu na žalost ni vedno razvidno na površini betona. Kljub dodatku v sestavi SCC se še vedno lahko pojavljajo površinske luknjice na vidni površini zato, ker samo delovanje dodatka nima vpliva na zajeti zrak med transportom in vgradnjo. Učinek delovanja dodatka na videz površine je potrebno predhodno preveriti na testnem polju skupaj s proizvodnjo, transportom in celotno tehnologijo vgradnje SCC betona.

Aerant oziroma »air-entraining admixtures« (AEA) pri SCC deluje kot površinsko aktivni dodatek, ki med mešanjem zniža površinsko napetost vode v mešanici in stabilizira vnesene zračne mehurčke. Koristen zračni sistem ne pomeni zgolj večjega skupnega deleža zraka, temveč predvsem veliko število drobnih, sferičnih in enakomerno razporejenih mehurčkov. Tipična velikost namerno vnesenih zračnih por je približno 10–1000 µm, povprečna velikost pa je pogosto okoli 100 µm (oziroma 0,1 mm). Aerant se betonu dodaja za doseganje odpornosti proti zmrzovanju in tajanju ob prisotnosti soli. Pri stopnji izpostavljenosti XF2 in XF4 je uporaba aeranta nujna, za stopnje XF1 in XF3 aerant ni nujno potreben.

Dodajanje aeranta v sestavi SCC vpliva tudi na reološko obnašanje SCC. Pri SCC lahko drobni mehurčki izboljšajo reologijo, saj delujejo v sestavi kot krogličnі ležaji in zmanjšajo notranje trenje med malto in grobim agregatom. Posebej koristni so mehurčki velikosti pod

450–500 µm. Optimalna količina zraka v sestavi lahko izboljša pretočnost, poveča kohezijo in stabilnost sestave [11]. Zaradi vnesenih mehurčkov se poveča navidezni volumen paste oziroma malte, kar lahko izboljša stabilnost in zmanjša tveganje segregacije. Aerant pomaga zmanjšati tudi občutljivost SCC na krčenje zaradi sušenja.

Vsi našteti faktorji lahko pripomorejo k izboljšanju vidne površine SCC, ker so povprečne velikosti zračnih por, vnesenih z aerantom, približno 0,1 mm pa teh por na vidni površini ni zaznati/videti. Večji zračni mehurčki pa so lahko neugodni, poslabšajo videz površine in ne prispevajo k želenemu samozgoščevalnemu učinku. Večinoma so večji mehurčki posledica vnesenega zraka v SCC skozi transport in predvsem ob vgradnji betona. Učinek aeranta na SCC je odvisen od doze, porazdelitve in velikosti zračnih por ter kompatibilnosti z drugimi dodatki predvsem PCE in cementom.

Pri vidnem SCC je zato potrebno preveriti ne le vsebnost zraka v sestavi, temveč tudi stabilnost zraka, velikost mehurčkov, vpliv na razlez, čas T500, V-lijak, segregacijo ter izdelati testno polje, kjer se bo preverilo in ocenilo izdelano vidno površino.

V literaturi so opisane tudi raziskave kombinacije aeranta in antipenilca [9]. Na prvi pogled je to nelogično, saj aerant dodaja zrak, antipenilec pa ga odstranjuje. V resnici pa cilj ni samo povečati ali zmanjšati skupni delež zraka, ampak preoblikovati sistem por. Dodatka naj bi v ustrezni kombinaciji povečala delež manjših por, ki so zaželene, večje pore pa naj bi učinkovito odstranil antipenilec. Pri vidnem betonu takšna kombinacija vodi v ustrezen sistem por, ki bo pozitivno deloval na reološko obnašanje svežega SCC in končni videz površine betona.

8 IZVEDBENI DEJAVNIKI – PROIZVODNJA, TRANSPORT, OPAŽ IN VGRAJEVANJE

Pri vidnem SCC je receptura le polovica zgodbe. Enaka receptura lahko da zelo različne rezultate glede na mešalec na betonarni, vrstni red dodajanja komponent, čas mešanja, transport, črpanje, temperaturo, opaž, ločevalno sredstvo in hitrost vlivanja. Zato moramo pri pripravi vidnega/arhitekturnega SCC vnaprej določiti protokole za izvajanje.

Prvi praktični dejavnik je robustnost SCC sestave. Receptura ne sme biti nastavljena na mejo sprejemljivosti. Če je razlez že v laboratoriju blizu zgornje meje in je segregacija komaj še sprejemljiva, bo na gradbišču ob majhni spremembi vlage ali temperature verjetno odpovedala. Bolje je izbrati sredino ciljnega območja z dobro stabilnostjo kot pa na primer maksimalni razlez brez rezerve.

Drugi dejavnik je časovna stabilnost. Preskus pri 5 minutah po mešanju ni dovolj. Pri realnem transportu in vgrajevanju je treba preveriti lastnosti po 30, 60 in po potrebi 90 minutah: razlez, čas T500, V-lijak, L-box/J-ring, segregacijo, vizualno stabilnost, vsebnost zraka, temperaturo in gostoto. Za vidni beton je zelo pomembno, da vse šarže pridejo do opaža v podobnem stanju. Če se prva šarža vgrajuje pri 710 mm, tretja pa pri 620 mm in večjem času T500, se lahko razlika pokaže na površini kot vidna nepravilnost.



Slika 5: Primer vgradnje s kiblo z gumijastim izpustom, stolp Kristal Rogaška, vir: inženirski biro Ponting.

Preglednica 8: Primerjava načinov vgradnje za vidni SCC.

Način vgradnje	Ocena za vidni beton	Glavne prednosti	Glavna tveganja
Črpanje od spodaj skozi priklop na opažu.	najboljša možnost	Ni zajema zraka ob vgradnji, enakomeren dvig betona, zelo dobra površina.	visok opažni tlak, potreben poseben priklop in tesen opaž, mesto priklopa ostane vidno.
Potopljena črpalna cev / kontraktor od zgoraj.	zelo dobra možnost	Malo prostega pada, manj površinskih luknjic.	Cev mora ostati potopljena, pozornost pri prestavljanju cevi.
Kibla z gumijastim izpustom.	dobra, če je pravilno izvedena	Malo prostega pada, primerna za manjše količine in nižje elemente.	Čakanje betona v kibli, prekinjen tok, netesna zapora.
Neposredno iz žleba ali z višine.	manj ugodno za vidni beton	Enostavno.	več zajetega zraka, segregacija, več luknjic in potencialno lis.
Prosti pad v opaž.	neugodno	Hitro.	zrak, segregacija, udarne cone, slabša površina.

Tretji dejavnik je vlaga agregata. Pri SCC, zlasti z drobljenim 0/4 peskom, lahko nekaj litrov efektivne vode na kubični meter spremeni mešanico iz stabilne v segregirano ali iz tekoče v lepljivo. Zato mora betonarna imeti redno kontrolo vlage peska in grobega agregata, sprotne korekcije vode ter jasen protokol za izvajanje korekcij dodatkov. Naknadno dodajanje vode na gradbišču je za vidni SCC praviloma nesprejemljivo.

Četrti dejavnik je opaž. SCC lahko daje izjemno površino, vendar ne more popraviti slabega opaža. Opaž mora biti tog, čist, tesen, ustrezno pripravljen in združljiv z ločevalnim sredstvom. Ločevalno sredstvo mora biti ustrezno nanešeno, praviloma se brizga na opažno površino v dovolj tankem nanosu. Pri visokih stenah ali stebrih moramo upoštevati opažni pritisk. Nosilnost opažev je pomembna. Na bočni pritisk opaža močno vplivajo reologija in tiksotropija SCC, hitrost vlivanja in višina, temperatura betona in okolice, relativna vlaga ter sama geometrija opaža [12].

Peti dejavnik je način vgrajevanja (preglednica 8). Način vgradnje ima pri vidnem SCC neposreden vpliv na kakovost in videz površine. SCC ne smemo vgrajevati z velike višine, saj prosti pad, udarjanje betona v armaturo ali padanje v že vgrajen beton, povečajo zajem zraka in lahko povzročijo dinamično segregacijo. Ker SCC ni vibriran, mora zajeti zrak iz betona izhajati sam, kar je odvisno od viskoznosti, kohezivnosti, hitrosti dviga betona v opažu, tipa opaža in ločevalnega sredstva. Najugodnejši način vgradnje za vidne vertikalne elemente je črpanje od spodaj skozi opažni priklop, saj beton mirno potiska maso navzgor, brez prostega pada in z minimalnim zajemom zraka. Zelo dobra alternativa je vgradnja s potopljeno cevjo oziroma kontraktorjem, kjer mora biti izpust cevi ves čas pod površino svežega betona. Kibla z gumijastim izpustom (slika 5) je primerna le za nižje elemente in če je izpustno cev mogoče spustiti med armaturo. Pri vseh načinih je bistveno, da je vgradnja kontinuirana, da ni nepotrebnega prostega pada in da beton ne vnaša dodatnega zraka, ki bi se kasneje pokazal kot površinske luknjice, lise ali neenakomerna površina.

Šesti dejavnik je vodoravni tok betona. Ker je SCC tekoč, se pogosto misli, da je dovolj vgrajevanje betona iz ene lokacije, saj se beton v opažu daleč razliva. Pri SCC je predolg vodoravni tok betona ena pomembnejših nevarnosti. SCC se mora razlivati in teči, vendar ni zaželeno, da mora od mesta vgradnje do skrajnega konca opaža prepotovati predolgo razdaljo. Nekaj horizontalnega toka je koristno, ker pomaga zraku izhajati iz betona. Priporočena največja razdalja od mesta vgradnje je 10 m. Pri daljši razdalji se zrak slabo izloča in lahko se pojavi dinamična segregacija.

Predolg vodoravni tok SCC od mesta vgradnje lahko povzroči, da se mešanica med razlivanjem ne obnaša več kot homogena celota. Grobi agregat zaradi trenja in zagozdenja zaostaja, bolj tekoča pasta oziroma malta pa potuje naprej. Posledica so dinamična segregacija, lokalne razlike v sestavi betona, večja možnost praznin, por neodzračenosti, sledi izločanja vode, sledi toka betona in neenakomerne površine. Pri vidnih betonih je to še posebej problematično, saj se razlike v sestavi in druge nepravilnosti neposredno pokažejo na opažni površini. Zato pri SCC ni cilj, da beton teče čim dlje, temveč da je mesto vgradnje izbrano tako, da beton opaž zapolni s kontroliranim in čim bolj enakomernim tokom. Kot ukrep za izboljšanje površine oziroma zmanjšanje zračnih luknjic na vidni površini je skrajšanje dolžine toka betona od mesta vgradnje na približno 5 m.

9 PREDNOSTI IN SLABOSTI SCC PRI VIDNIH BETONIH

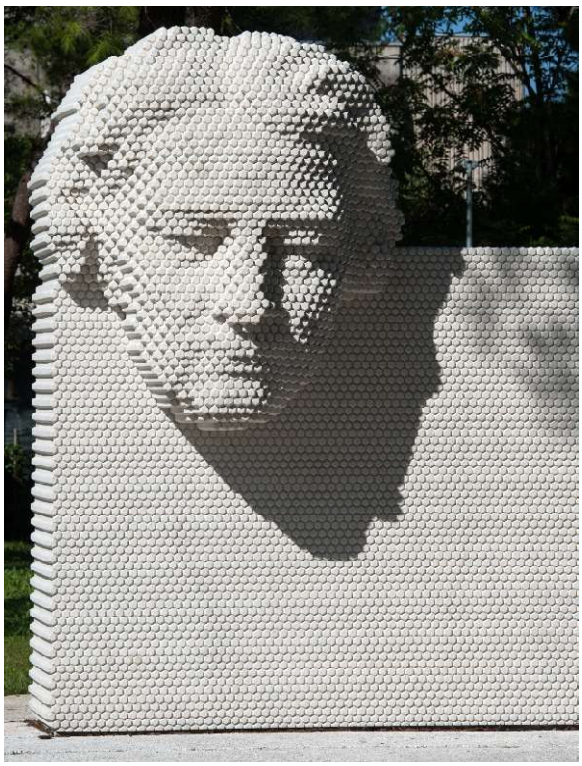
Največja prednost SCC je odprava vibriranja. To zmanjša hrup, fizično delo, potrebo po dostopu z vibratorjem in tveganje za lokalne napake zaradi človeškega faktorja. Pri kompleksnih opažih, gostih armaturah, tankih stenah ali visokih elementih je SCC pogosto tehnološko najbolj racionalna izbira. Poleg tega lahko dobro projektiran SCC zaradi večjega deleža paste in finih delcev bolje reproducira teksturo opaža, sploh kadar je površina reliefna ter doseže bolj gladko površino.

Druga prednost je boljše zapolnjevanje detajlov. Pri vidnem/arhitekturnem betonu so robovi, vogali, utori, teksturirani vložki in površine, kjer se uporabljajo za odtise matrice pogosto kritični. Vibrirani beton lahko na takih mestih pore neodzračenosti ujame ali jih zaradi neenakomernega vibriranja premakne v vidne cone. SCC ima potencial, da zrak učinkoviteje izrine, vendar samo, če je viskoznost pravilna in če opaž ne zadržuje por neodzračenosti zaradi neustreznega ločevalnega sredstva.

Tretja prednost je možnost uporabe mineralnih dodatkov in filerjev za oblikovanje reologije. GGBS, apnenčev filer, mikrosilika, elektrofiltrski pepel in drugi praškasti dodatki omogočajo optimiziranje paste. Pri vidnem betonu lahko to pomeni bolj zaprto površino, manj krvavenja in manj segregacije. Vendar moramo vsak material obravnavati glede na njegovo specifično površino, mineralogijo, obliko delcev in kompatibilnost s PCE.



Slika 6: Poševna fasada Muzej sodobne umetnosti, Ljubljana, Vir: splet.



Slika 7: Spomenik Franceta Prešerna v Črni Gori.

Slabosti SCC so povezane predvsem z občutljivostjo. SCC je manj toleranten do nihanja vode, vlage agregata, finih delcev, temperature in mešanja. Pri običajnem betonu lahko majhno odstopanje pogosto popravi vibriranje, pri SCC pa vibriranja ni. Če se pojavi blokiranje, segregacija ali prevelika vsebnost zraka, popravek že vgrajenega betona v opaž ni mogoč.

Pomembno tveganje je tudi opažni pritisk. Ker je SCC tekoč obremeni opaž v neugodnih pogojih bližje hidrostatičnemu pritisku kot običajni beton. To je pomembno predvsem pri visokih stenah in stebrih, kjer sta hitrost vlivanja in tiksotropno obnašanje odločilna. Pri vidnem betonu moramo, ne le zaradi varnosti, temveč zaradi estetike, zahtevati večjo togost opaža.

Drugo tveganje so površinske luknjice. Zelo tekoča mešanica ne pomeni nujno manj por neodzračenosti. Če PCE stabilizira zračne mehurje ali če ločevalno sredstvo in opaž spodbujata zadrževanje por neodzračenosti, se lahko pojavi večje število površinskih luknjic (bugholes), kot pri dobro zgoščenem/vibriranem betonu. Zato je pri vidnem SCC smiselno preskušati tudi vsebnost zraka, ne le razlez in ostalih parametrov svežega SCC.

10 PRIMERI UPORABE SCC

Prvi primer uporabe vidnega belega SCC je fasada Muzeja sodobne umetnosti Metelkova v Ljubljani (slika 6), ki ga je projektiral biro Groleger arhitekti. Muzej je bil dokončan 2011 leta. Fasada dozidanega dela je zasnovana kot dvoslojni ovoj, zunanja del je kompozicija poševnih sten iz vidnega belega SCC, notranji zidovi razstavnih prostorov pa so vertikalni.

V sklopu predhodnih preiskav smo izdelali recepturo in preverili lastnosti svežega SCC. Pred začetkom gradnje se je na betonarni GPG izvedlo poskusno betoniranje in izdelalo dve testni sten (Mock up), ki sta služili kot referenca. Beton se je vgrajeval v opaž skozi opažne ventile na dnu opaža.

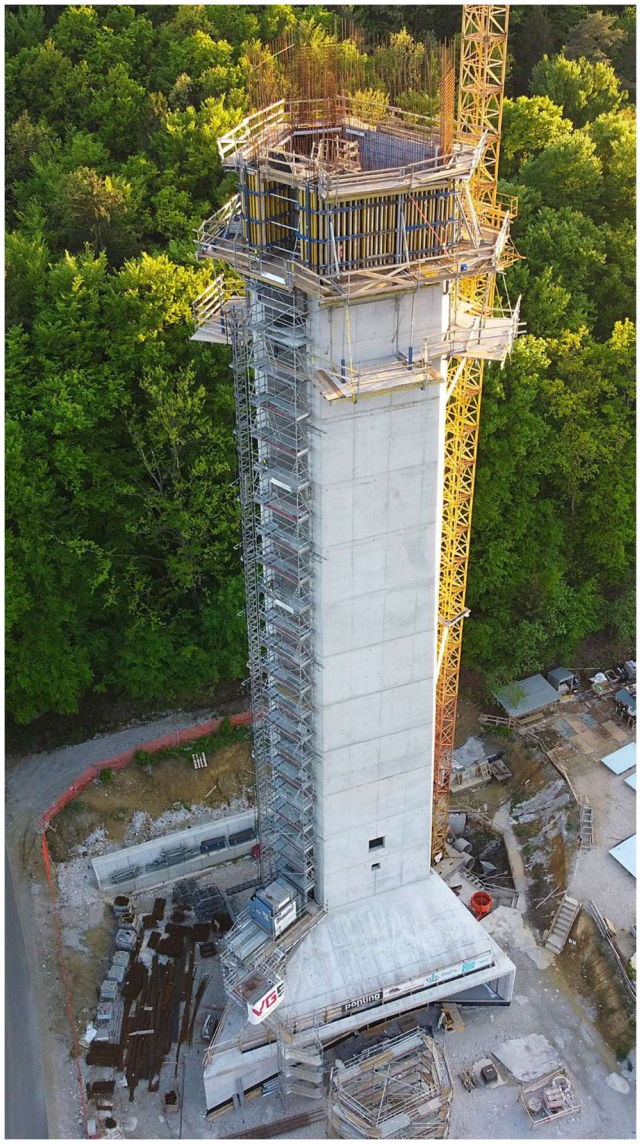
Drug primer uporabe SCC je izdelava spomenika Franceta Prešerna (slika 7). Spomenik je bil izdelan v podjetju Žurbi d.o.o. in kasneje transportiran v Podgorico v Črni Gori. SCC je bil pripravljen na betonarni Bordax d.o.o. v Ljubljani in večkrat preverjen, izdelano je bilo tudi testno polje kot preveritev nosilnosti opaža. SCC se je v kalup vgrajeval s pomočjo potopljenega kontraktorja.



Slike: 8, 9, 10 in 11: Prikaz gradnje v različnih fazah in prerez 18 etaže, stolp Kristal Rogaška, vir: inženirski biro Ponting.

Tretji primer je 106 m visok stolp Kristal v Rogaški Slatini. Stolp sta zasnovala Inženirski biro Ponting in Korpnik produkcija. Glavni izvajalec je bil VG5 d.o.o., gradnja je trajala približno dve leti, Stolp je bil uradno odprt maja 2024. SCC se je v spodnjem delu stolpa vgrajeval z avtočrpalko in žerjavom s kiblo, v višje elemente, izven dosega črpalke, pa se je vgrajeval samo z žerjavom in kiblo. Zaradi dodatka regulatorja vezanja (Recover, GPC) v sestavi SCC je beton lahko več ur ohranjal reološke lastnosti. Nosilni steber stolpa spremenljivega šest-kotnega prereza (slika 11) je izveden iz 25 segmentov višine 3,85 m. Od višine približno 94,4 m navzgor so v steber vpete tri konzolne armiranobetonske plošče (kavarna in razgledišče). V rob stebra je vgrajeno panoramsko dvigalo, v stebru poteka še varnostno stopnišče z vmesnimi podesti ter servisnimi oziroma tehnološkimi etažami in instalacijskim jaškom.

Informacije vezane na gradnjo: Uporaba SCC kot rešitev za gosto armirane prereze je bila sprejeta 3 tedne pred izdelavo testnega polja in 4 tedne pred začetkom gradnje. Laboratorijsko smo pripravili 8 mešanic SCC. Na izbor primerne sestave SCC je imela največji vpliv hitrost dobave in razpoložljivost surovin, zato je bila kot polnilo izbrana žlindra (GGBS) namesto apnenčevega filerja (kamena moka Calplex VP). Tlačne trdnosti so dosegale projektirane vrednosti pri 7 dneh zato so končne trdnosti močno presežene. Tekoča mikrosilika je bila dodana sestavi preventivno za primer, da bi se uporabljal vertikalni cevovod za črpanje SCC, šele kasneje je ugotovljeno, da pušča sledi na vidni površini (»zebra efekt«). Ker je bil opažni sistem že dostavljen na gradbišče, ni bilo mogoče izvesti spremembe, da bi vgradnja SCC potekala skozi priklop na dnu opaža. Vgradnja SCC je tako potekala z avtočrpalko, ki je imela cev potopljeno v SCC in kiblo z gumijastim izpustom, kjer cev večinoma ni bila potopljena v SCC. Zahteve glede razreda vidnega betona so se med gradnjo spreminjale in prilagajale. Lastnosti SCC: razlez s posedom ciljni 720 mm, čas T500 okoli 3s, V lijak < 8 s, L box med 0,95 in 0,82.





Sliki 12 in 13: Prikaz stolpa med gradnjo in po zaključeni gradnji, vir: inženirski biro Ponting.

11 ZAKLJUČEK

SCC je pri vidnih oziroma arhitekturnih betonih zelo učinkovita tehnologija, vendar kakovostne površine ne zagotavlja samodejno. Njegova prednost je sposobnost zapolnjevanja opaža brez vibriranja, kar lahko zmanjša gnezda, izboljša oblitje armature in omogoči izvedbo zahtevnejših geometrij ter teksturiranih opažnih površin. Hkrati pa tekoča sestava SCC poveča občutljivost na segregacijo, krvavenje, sistem zračnih por, opažni pritisk in način vgradnje.

Ključno merilo za uspešen vidni SCC ni največji možni razlez, temveč stabilna samozgoščevalnost. To pomeni usklajeno kombinacijo nizke meje tečenja, ustrezne plastične viskoznosti, primerne tiksotropije in kontroliranega zračnega sistema. Razlez s posedom je zato le osnovni kazalnik. Za zanesljivo oceno so potrebni tudi čas T500, V-lijak, L-box ali J-ring, segregacijo, vsebnost zraka, gostoto, temperaturo in preverjanje časovne stabilnosti do trenutka vgradnje.

Pri sestavi SCC ima odločilen vpliv praškasti del sestave: filer, GGBS/GGBFS, mikrosilike ter pakirna gostota in granulometrija agregata. Pri kamnolomskih frakcijah so zaradi oglatosti, hrapavosti, variabilnega deleža finih delcev in nihanja vlage, tveganja večja kot pri rečnih agregatih, vendar lahko pravilno optimiziran agregatni skelet in kontroliran filer omogočita zelo stabilen beton. Cilj ni naključno povečevanje paste ali PCE, temveč uravnotežen volumen paste, ki zapolni praznine, zmanjša trenje in še vedno preprečuje segregacijo.

Kemični dodatki morajo biti uporabljeni kot del celotnega reološkega sistema. PCE omogoča tekočnost, VMA in stabilizator povečujeta robustnost in zadrževanje vode, antipenilec zmanjšuje neželene velike zračne mehurčke, aerant pa načrtno uvaja drobne zračne pore za trajnost in lahko vpliva tudi na reologijo. Noben dodatek ne nadomesti dobre granulometrije, pravilnega volumna paste in preverjene kompatibilnosti cementa, mineralnih in kemijskih dodatkov.

Pri vidnem SCC moramo projektirati celoten proces: proizvodnjo na betonarni, zaporedje mešanja, transport, kontrolo vlage, opaž, ločevalno sredstvo, način vgrajevanja, hitrost dviga betona v opažu, omejitev vodoravnega toka, nego in razopaževanje. Najbolj zanesljiva pot do kakovostne površine je poskusno testno polje izvedeno v realnih pogojih. Šele kombinacija laboratorijsko potrjene recepture, kontrolirane proizvodnje in pravilne izvedbe omogoča homogeno, tehnično zanesljivo in estetsko kakovostno vidno betonsko površino.

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33. SLOVENSKI KOLOKVIJ O BETONIH

Vpliv malih sprememb v sestavi SCC na njegovo obdelovalnost

Effect of small changes in the mix-proportion of SCC on its workability

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Povzetek

V članku prikazujemo rezultate predhodnih preiskav svežega samozgoščevalnega betona (SCC), ki je namenjen za zapolnjevanja praznih prostorov med zabojniki v silosu za odlaganje nizko in srednje radioaktivnih odpadkov (NSRAO). Obravnavane preiskave so del obširnega projekta „Študija proizvodnje, vgradljivosti in karakteristik končnih betonskih mešanic kot polnil med odlagalnimi zabojniki N2d v silosu odlagališča NSRAO“. Za projektiranje sestav SCC smo uporabili modificirano empirično metodo. Namen teh preiskav je bil, da poiščemo optimalno sestavo SCC glede njegove obdelovalnosti, oziroma njegove sposobnosti pretočnosti in prehajanja ter viskoznosti. Rezultati kažejo na viden vpliv že malih sprememb v sestavi SCC na njegovo odbelovalnost (pretočnost, prehajanje in viskoznost).

Abstract

In this paper, we present the results of preliminary investigations of fresh self-compacting concrete (SCC) intended for filling the empty spaces between containers in a silo for the disposal of low- and intermediate-level radioactive waste (LILW). The investigations in question are part of a larger project titled "Study of the production, workability, and characteristics of ready-mix concrete as backfill material between N2d storage containers in the LILW storage silo." We used a modified empirical method to design the SCC mix-proportions. The purpose of these investigations was to determine the optimal mix-proportion of the SCC in terms of its workability—specifically, its flowability, passing ability and viscosity. The results indicate that even small changes in the mix-proportion of SCC have a significant effect on its workability (flowabilit, passing ability, and viscosity).

Ključne besede: samozgoščevalni betona (SCC), sestava SCC, odelovalnost, pretočnost, viskoznost, sposobnost prehajanja
Keywords: self-compacting concrete (SCC), SCC mix-proportion, workability, flowability, viscosity, passing ability

1. UVOD

V okviru projekta „Študija proizvodnje, vgradljivosti in karakteristik končnih betonskih mešanic kot polnil med odlagalnimi zabojniki N2d v silosu odlagališča NSRAO“ (skrajšano: Študija PB) [1, 2], ki ga financira ARAO-Agencija za radioaktivne odpadke, smo v okviru 2. faze [2] izvedli predhodne laboratorijske preiskave na 14 sestavah samozgoščevalnega betona (SCC).

Preglednica 1: Mesečni povprečni rezultati preskusov cementa CEM II 32,5.

Test date	Water demand	Setting time		Compressive strength		Specific surface (Blaine)	SO_3
		initial	final	2 days	28 days		
	(%)	(min)	(min)	(MPa)	(MPa)	(cm^2/g)	(%)
11.02.2025	28,4	192	232	16,6	46,2	4715	2,54
16.04.2025	27,6	251	303	14,3	43,6	4902	2,77
3.09.2025	28,4			15,5		4230	2,6
8.09.2025	28,2	259	305	14,7		4020	2,47
Average	**28,2**	**223**	**268**	**15,6**	**45,4**	**4754**	**2,7**

Glavni namen Študije PB je razvoj optimalne sestave betona, ki bo sposoben enakomerno zapolniti vse vmesne prostore med zabojniki odlagalnega silosa. Ker je prisotnost ljudi na mestu vgrajevanja omejena (ALARA – As Low As Reasonably Achievable), zato bomo pri razvoju tehnologije polnilnega betona (PB) in vgradnji sledili principu ALARA in poskušali razviti PB ter tehnologijo vgrajevanja, da bo možno iz čim manj mest vgrajevanja zapolniti vse medprostore med dvema vrstama zabojnikov po celotni površini silosa. Glede na te predpostavke, smatramo, da bi bil samozgoščevalni beton (SCC) najbolj primeren za zapolnjevanje prostorov med zabojniki v odlagalnem silosu.

Obstaja več metod projektiranja sestav SCC. Shi [3] je metode projektiranja klasificiral v pet kategorij: (1) empirična metoda projektiranja [4 – 7], (2) metoda tlačne trdnosti [8, 9], (3) metoda zaprtega pakiranja agregata [10 – 16], (4) metoda projektiranja mešanice, ki temelji na statistični metodi [17 - 19] in (5) metoda projektiranja mešanice, ki temelji na metodi reologije paste [20 - 22].

Shi zaključuje, da je projektiranje mešanice ključno za doseganje visoko kakovostnega SCC. Dobra metoda projektiranja mešanice SCC bi morala upoštevati: (1) široko uporabnost; (2) močno robustnost za variabilne osnovne materiale; (3) tehnične zahteve; (4) trajnostnost in (5) ceno. Doslej nobena metoda v popolnosti ne izpolnjuje pet priporočil. Torej, primeren model bi moral biti izbran glede na specifične zahteve.

Glede na naše izkušnje, bi za naš primer bila najprimernejša modificirana empirična metoda projektiranja. Ta metoda je lahko sledljiva, vendar so potrebni intenzivni laboratorijski preskusi z razpoložljivimi osnovnih materialih, da se dobijo zadovoljive sestave. Empirična metoda projektiranja temelji na empiričnih podatkih, ki vključujejo vsebnost grobih in finih agregatov, cementnih materialov ter superplastifikatorja, da se določijo začetne sestave. Optimalne sestave, glede na zahtevane lastnosti, se dobijo na osnovi številnih poskusnih mešanicah in ponavljanja.

2. IZBOR OSNOVNIH MATERIALOV

2.1 Cement

Že nekaj časa potekajo intenzivne raziskave na področju uporabe alternativnih veziv, ki bodo v prihodnosti, v določenem obsegu nadomestila konvencionalna veziva na osnovi portlandskega klinkerja. Prav tako se raziskuje, kateri mineralni dodatki bi lahko v prihodnosti nadomestili trenutno uporabljane materiale kot sta plavžna žlindra in filtrski pepel. Hkrati pa potekajo raziskave novih proizvodenj cementa, ki bodo v prihodnosti omogočile ogljično nevtralno proizvodnjo in njeno integracijo v krožni model gospodarstva.

Ker se bo odlagalni silos predvidoma polnil nekaj desetletij, se bodo glede na zgoraj opisane razvojne trende, v tem času spreminjale vrste cementov in uporabljale nove vrste. Na osnovi strokovnega posveta v cementarni Alpacem Slovenija o vrsti cementa, ki bi ga uporabili v okviru študije in bi se uporabil za pripravo betona za prva polnjenja silosa smo se odločili za uporabo dolgoročno dosegljiva cementa:

- CEM II/C-M (S-LL) 32,5 R (skrajšano CEM II 32,5) in
- CEM II/C-M (S-LL) 42,5 N (skrajšano CEM II 42,5).

Oba cementa sta proizvedena v skladu s SIST EN 197-5:2021 Cement - 5. del: Portlandski kompozitni cement CEM II/CM in kompozitni cement CEM VI.

Laboratorij proizvajalca Alpacem izvaja redne preskuse cementov v okviru notranja kontrole proizvodnje. Nekaj teh rezultatov preskusov cementa CEM II 32,5 podajamo v preglednici 1, cementa CEM II 42,5 pa v preglednici 2.

2.2 Kameni agregati

Z namenom, da dosežemo dobro vgradljivost SCC in zmanjšanja modula elastičnosti smo se odločili za uporabo posameznih frakcij rečnega agregata – naravnega savskega proda iz separacije Hotič, ki ima certifikat o skladnosti tovarniške kontrole proizvodnje

Preglednica 2: Mesečni povprečni rezultati preskusov cementa CEM II 42,5.

Month	Water demand	Setting time		Compressive strength			Specific surface (Blaine)	SO_3
		initial	final	1 day	2 days	28 days		
	(%)	(min)	(min)	(MPa)	(MPa)	(MPa)	(cm^2/g)	(%)
2025-01	29,5	194	232	13,2	22,8	53,7	4727	2,61
2025-02	29,2	205	251	13,1	22,8	52	4670	2,68
2025-03	29,8	202	247	12,7	22,4	51,5	5083	2,60
2025-04	29,8	221	272	12,7	21,8	50,6	5043	2,59
2025-05	29,6	200	244	12,4	23,7	52,7	5070	2,62
2025-06	29,7	206	249	11,5	23,4	53,9	5042	2,61
2025-07	30,0	205	252	12	22,7	50,9	5013	2,62
2025-08	29,9	197	238	12,2	21,8	49,8	5052	2,62
2025-09	29,8	203	242	12	22,8		5000	2,69
Average	**29,7**	**204**	**249**	**12,4**	**22,6**	**51,9**	**5005**	**2,62**

Preglednica 3: Sestava cementne paste.

komponente	merska enota	količine
cement	(g)	1170
kamena moka VP	(g)	295
suspenzija mikrosilike	(g)	80,68
voda	(g)	374
superplastifikator RC	(g)	10,49
vodocementno razmerje v/c	(-)	0,36

po EN 12620:2002+A1:2008. Frakcije tega agregata, ki smo jih uporabili za pripravo SCC so: 0-2 mm (drobljena frakcija), 0-4, 4-8, in 8-16 mm.

Alternativno smo uporabili drobljeni apnenčev agregat iz separacije Calcit Kamnik (frakcije: 0-2, 4-8, in 8-16 mm).

Na osnovi rezultatov preiskav, ki smo jih izvršili v okviru projekta »Študija proizvodnje, vgradljivosti in karakteristik končnih polnilnih in tesnilnih malt za odlagalni zabojnik N2d«[23] smo med štirimi vrstami kamene moke, iz proizvodnje Calcit-a, kot najprimernejšo izbrali kameno moko CalPlex VP, ki smo jo uporabili tudi za pripravo polnilnega betona (SCC).

2.3 Mineralni dodatki

V okviru laboratorijskih preiskav smo v vseh sestvah uporabili mikrosiliko v suspenziji z namenom, da izboljšamo pretočnosti in čim boljše samoizravnavo svežega SCC.

2.4 Kemijski dodatki

Glede na kriterije kakovosti, ki jih mora doseči polnilni beton (SCC) v svežem in strjenem stanju smo pri prvih mešanicah uporabili kemijske dodatke, ki smo jih uporabili v okviru do sedaj izvedenih projektov. Pri tem pa smo se zavedali, da v predmetni študiji uporabljamo druge vrste cementov (mešani cementi), ki so bolj kompleksni in je njihova odzivnost na dodatke lahko povsem drugačna. Predvsem zaradi zahtevnih reoloških lastnosti svežega SCC smo v okviru laboratorijskih preiskav iskali optimalno kombinacijo izbranih kemijskih dodatkov.

3. CEMENTNE PASTE

Pred začetkom projektiranja sestav SCC smo preiskali cementne paste, z namenom, da določimo najučinkovitejši superplastifikator glede na obdelovalnost cementne paste z izbranima vrstama cementa CEM II 32,5 in CEM II 42,5. Dodatno smo preiskali tudi paste s cementoma CEM I 42,5 N SR0 (skrajšano CEM I) in CEM III/B 32,5 N – LH/SR (skrajšano CEM III), z namenom primerjave učinkovitosti uporabljenih superplastifikatorjev na obdelovalnost cementne paste z različnimi vrstami cementa. Superplastifikatorje na bazi polikaboksilatov smo izbrali glede na naše izkušnje, ki smo jih pridobili v praksi in v okviru študij betonov za sekundarno

oblogo [24], kontraktorskega betona za diafragmo [25] in polnilne malte odlagalnih zabojnikov [23].

V preglednici 3 podajamo sestavo cementne paste, pri čemer smo spreminjali vrsto cementa in superplastifikatorja RC. V vseh pastah so vse ostale komponente enake (kamena moka VP, suspenzija mikrosilike in voda). Konstantno je tudi vodocementno razmerje v/c = 0,36.

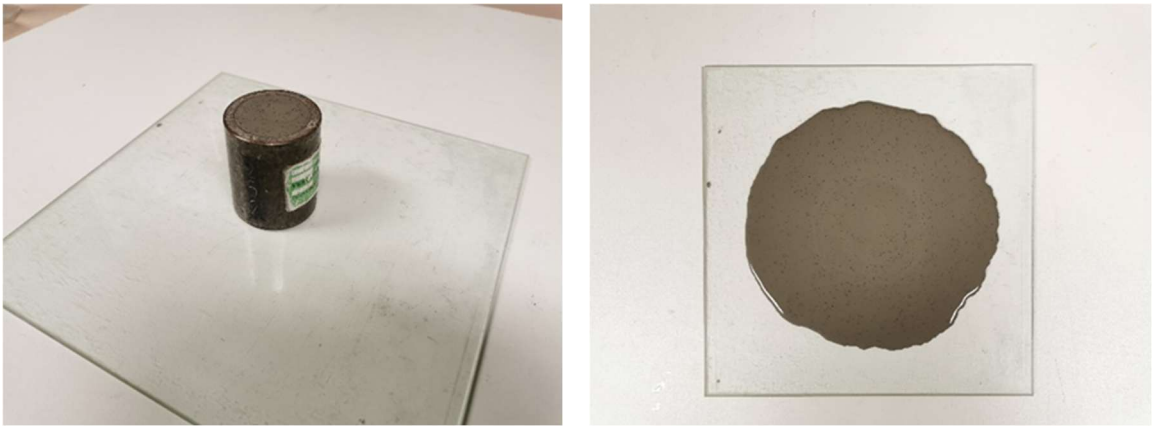
V preglednici 4 podajamo za posamezno kombinacijo cementa in superpastifikatorja RC rezultate meritev razleza cementne paste. Meritev smo izvajali po metodi, ki je podana v SIST EN 445:2008 Injekcijska masa za prednapete kable – Preskusne metode. Merili smo premer razleza paste (slika 1(b)), v dveh pravokotnih smereh, na ravni površini, po dvigu kalupa valjaste oblike (1 (a)) z višino 60 mm in notranjim premerom 39 mm, ki je bil napolnjen s pasto.

V sliki 2 so v grafični obliki prikazane povprečne vrednosti razleza za posamezno cementno pasto z različnimi kombinacijami vrste cementa in superplastifikatorja RC.

Med vsemi preiskanimi cementnimi pastami izkazujejo relativno najboljšo obelovalnost (največji razlez) paste s cementom CEM II 32,5 in vsemi tremi superplastifikatorji, med katerimi izstopa RC 896. To kombinacijo cementa in superplastifikatorja smo največkrat uporabili v sestavah SCC. Med pripravo in preskusom nismo zaznali pri nobeni pasti segregabilnost in naknadno izločanje vode (krvavenje), ki smo ju ocenjevali vizualno.

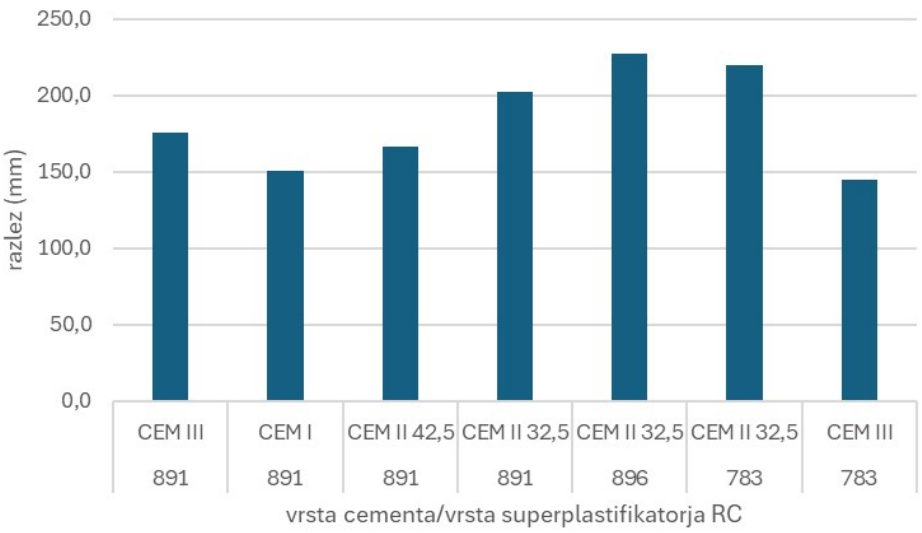
4. SESTAVE POLNILNIH BETONOV (SCC)

Sestave polnilnih betonov (SCC), ki smo jih pripravili in preiskali v okviru Študije PB podajamo v preglednici 5 (a): od 1. do 7. sestave (od B do B-5) in v preglednici 5 (b): od 8. do 14. sestave (od B-6 do A-2).



(a) (b)

Slika 1: (a) Napolnjen kalup valjaste oblike s cementno pasto pred dvigom; (b) razlez cementne paste po dvigu kalupa..



Slika 2: Povprečne vrednosti razleza cementne paste z različnimi kombinacijami vrste cementa in superplastifikatorja RC

Preglednica 4: Rezultati meritev razleza cementne malte.

datum meritve	super - rplastifikator Pantarhit RC	vrsta cement	razlez (mm)	
			medsebojno prevokotna premera	povprečno
15.10.2025	891	CEM III	175/177	176,0
21.10.2025	891	CEM I	151/151	151,0
21.10.2025	891	CEM II 42,5	134/134	166,5
21.10.2025	891	CEM II 32,5	200/205	202,5
22.10.2025	896	CEM II 32,5	230/225	227,5
5.11.2025	783	CEM II 32,5	220/220	220,0
5.11.2025	783	CEM III	145/145	145,0

Preglednica 5(a): Sestave SCC – od 1. do 7. sestave (od B do B-5).

komponente betona		merska enota	zaporedna številka sestave						
			1	2	3	4	5	6	7
			oznaka sestave						
			B	B-2	A-1	C	B-3	B-4	B-5
			6.10.2025	7.10.2025	8.10.2025	9.10.2025	10.10.2025	13.10.2025	14.10.2025
cement CEM II/C-M (S-LL) 32,5 R		(kg)	420	420	420	420	-	-	-
cement CEM II/C-M (S-LL) 42,5 N		(kg)	-	-	-	-	420	420	420
mikrosilika v suspenziji (slurry)		(kg)	20	20	20	20	20	20	20
kamena moka Calcit	CalPlex VP	(kg)	110	120	120	120	120		120
	CalPlex 15	(kg)	-	-	-	-	-	120	-
super - - plastifikatorji	RC 896	(kg)	3,6	2,6	2,1	-	2,5	2,5	2,5
	Sika ViscoCrete 5090	(kg)	-	-	-	2,1	-	-	-
	Dynamon SX	(kg)	-	-	-	-	-	-	-
stabilizatorja	Stabilaser DF	(kg)	1,6	1,6	1,6	1,4	1,1	1,2	1,2
	Viscofluid SCC/10	(kg)	-	-	-	-	-	-	-
zavlačevalec	RECOVER	(kg)	1,4	1,4	1,4	1,4	1,4	1,4	1,4
suhe frakcije naravnega, prodnatega agregata iz separacije Hotič	0 - 2 mm drobljeni	(%)	-	-	-	-	-	-	-
		(kg)	-	-	-	-	-	-	-
	0 - 4 mm	(%)	60,0	60,0	40,0	60,0	60,0	60,0	60,0
		(kg)	933,27	933,51	618,45	927,78	927,84	927,79	927,79
	4 - 8 mm	(%)	14,0	15,0	17,0	15,0	15,0	17,0	17,0
		(kg)	217,76	233,38	270,57	231,95	231,96	262,87	262,87
	8 - 16 mm	(%)	26,0	25,0	25,0	25,0	25,0	23,0	23,0
		(kg)	404,42	388,96	378,80	386,58	386,60	355,65	355,65
suhe frakcije drobljenega apnenčevega agregata iz separacije Calcit	0 - 2 mm	(%)	-	-	18,0	-	-	-	-
		(kg)	-	-	281,41	-	-	-	-
	4 - 8 mm	(%)	-	-	-	-	-	-	-
		(kg)	-	-	-	-	-	-	-
	8 - 16 mm	(%)	-	-	-	-	-	-	-
		(kg)	-	-	-	-	-	-	-

Pri 11 sestavah smo uporabili cement CEM II 32,5 in le pri 3 sestavah CEM II 42,5. Za tako odločitev obstajajo na splošno trije razlogi: (1) dobra kompatibilnost z izbranim superpalstifikatorjem (3. poglavje), (2) ker je v primerjavi s CEM II 42,5 bolj groboznat, oziroma ima manjšo specifično površino (preglednica 1) pričakujemo med strjevanjem betona, pri enaki količini cementa, razvoj relativno nižje hidratacijske toplote in (3) pri istem vodovezivnem razmerju pričakujemo, da bo tlačna trdnost betona nekoliko nižja, a še dovolj visoka, da bo dosežen zahtevani trdnostni razred C25/30; zaradi nižje trdnosti pa pričakujemo tudi manjši modul elastičnosti, kar je ugodno za namensko uporabo. Na podlagi empiričnih izkušenj smo izbrali enako količino cementa v vseh sestavah (420 kg/m^3

Preglednica 5(b): Sestave SCC – od 8. do 14. sestave (od B-6 do A-2).

komponente betona		merska enota	zaporedna številka sestave						
			8	9	10	11	12	13	14
			oznaka sestave						
			B-6	B-7	B-8	B-9	B-9-MP1	B-10	A-2
			15.10.2025	16.10.2025	22.10.2025	22.10.2025	30.10.2025	3.11.2025	6.11.2025
cement CEM II/C-M (S-LL) 32,5 R		(kg)	420	420	420	420	420	420	420
cement CEM II/C-M (S-LL) 42,5 N		(kg)	-	-	-	-	-	-	-
mikrosilika v suspenziji (slurry)		(kg)	20	20	20	20	20	20	20
kamena moka Calcit	CalPlex VP	(kg)	120	130	130	130	130	130	130
	CalPlex 15	(kg)	-	-	-	-	-	-	-
super - - plastifikatorji	RC 896	(kg)	2,5	2,5	2,5	2,5	-	2,5	2,5
	Sika ViscoCrete 5090	(kg)	-	-	-	-	-	-	-
	Dynamon SX	(kg)	-	-	-	-	2,58	-	-
stabilizatorja	Stabilaser DF	(kg)	1,2	1,1	1,1	1,1	-	1,1	1,1
	Viscofluid SCC/10	(kg)	-	-	-	-	3,23	-	-
zavlačevalec	RECOVER	(kg)	1,4	1,5	1,5	1,5	1,5	1,5	1,5
suhe frakcije naravnega, prodnatega agregata iz separacije Hotič	0 - 2 mm drobljeni	(%)	-	-	-	15,0	15,0	15,0	15,0
		(kg)	-	-	-	231,32	231,37	231,32	231,32
	0 - 4 mm	(%)	48,0	60,0	60,0	45,0	45,0	45,0	45,0
		(kg)	742,23	921,87	921,87	691,40	691,53	691,40	691,40
	4 - 8 mm	(%)	17,0	19,0	21,0	19,0	19,0	21,0	-
		(kg)	262,87	291,93	322,66	291,93	291,98	322,66	-
	8 - 16 mm	(%)	23,0	21,0	19,0	21,0	21,0	19,0	-
		(kg)	355,65	322,66	291,93	322,66	322,71	291,93	-
suhe frakcije drobljenega apnenčevega agregata iz separacije Calcit	0 - 2 mm	(%)	12,0	-	-	-	-	-	-
		(kg)	187,63	-	-	-	-	-	-
	4 - 8 mm	(%)	-	-	-	-	-	-	21,0
		(kg)	-	-	-	-	-	-	325,05
	8 - 16 mm	(%)	-	-	-	-	-	-	19,0
		(kg)	-	-	-	-	-	-	294,10

vgrajenega betona), ki nam zagotavlja dobro obdelovalnost in vgradljivost SCC.

V vseh sestavah smo dodali enako količino mikrosilike (suspenzije), ki nam prispeva k dobri obdelovalnosti in pretočnosti svežega SCC, izboljšuje pa tudi sprijemljivost cementnega kamna z okrogloznatim agregatom zaradi zmanjšanja poroznosti tranzicijske cone.

Projektirano totalno vodovezivno razmerje je v vseh sestavah enako $(v/v)_{tot}$ = 0,51. Pri tem izračunu je vezivna komponenta privzeta kot vsota količine cementa in suhega dela suspenzije mikrosilike v 1 m^3 vgrajenega betona.

Količino kamene moke smo povečevali od 110 do 130 kg/m^3 vgrajenega betona. V vseh sestavah, razen ene, smo uporabili kameno moko CalPlex VP, ki smo jo že uporabili v sestavi kontraktorskega betona za diafragmo [25].

Na osnovi rezultatov preskusa cementne paste smo izbrali superplastifikator Pantarhit RC 896, proizvajalca HaBe (3. poglavje). V dveh sestavah smo dodali superplastifikatorja drugih dveh proizvajalcev: Sika (Sika ViscoCrete 5090) in Mapei (Dynamon SX).

Stabilizator Stabilaser DF smo dodali v vse sestave, razen sestave, kjer smo dodali superplastifikator Dynamon SX, pri kateri smo dodali stabilizator istega proizvajalca Mapei (Viscofluid SCC/10). Količino stabilizatorja Stabilaser DF smo zmanjševali od 1,6 na 1,1 kg/m^3 vgrajenega betona.

Zavlačevalec RECOVER, ki smo ga prav tako že uporabili v sestavi kontraktorskega betona za diafragmo [25], smo dodali v vse sestave SCC v količini 1,4 kg, ki smo jo povečali na 1,5 kg/m^3 vgrajenega betona.

Preiskave so pokazale, da je za dobro obdelovalnost in vgradljivost SCC najprimernejša sestava z vsemi frakcijami okroglozrnatega rečnega agregata. Z dodano drobljeno frakcijo 0-2 mm tega agregata pa smo dosegli večjo kompaktnost sveže betonske mešanice, ki ne vpliva na njeno obdelovalnost in vgradljivost.

Preglednica 6(a): Rezultati preiskav svežih mešanic polnilnega betona (SCC) - za sestave od 1. do 7. (od B do B-5).

vrsta preskusa svežega polnilnega betona (SCC)	merjena lastnost	čas po zamešanju	merska enota	zaporedna številka sestave						
				1	2	3	4	5	6	7
				oznaka sestave						
				B	B-2	A-1	C	B-3	B-4	B-5
				6.10.2025	7.10.2025	8.10.2025	9.10.2025	10.10.2025	13.10.2025	14.10.2025
temperatura svežega betona	T_b	po 5 min	(°C)	17,5	n.d.	n.d.	16,8	17,3	18,0	16,9
temperatura zraka	T_z	po 5 min	(°C)	14,0	n.d.	n.d.	15,8	15,5	16,4	14,1
vodovezivno razmerje po SIST 1026:2016,NC	$(v/v)_{tot}$	po 5 min	(-)	0,430	0,453	0,475	0,477	0,494	0,496	0,470
vsebnost zraka po SIST EN 12350-7:2019, tč.5	A_1	po 5 min	(% v/v)	1,4	2,2	1,7	1,8	1,5	1,8	1,9
J-obroč po SIST EN 12350-12:2010	SFJ	po 10 min	(mm)	720/775	695/690	660/610	630/620	700/670	700/690	705/700
	t_{500J}	po 10 min	(s)	2,67	3,29	2,25	1,41	1,18	1,95	1,15
	PJ	po 10 min	(mm)	n.d.	10,25	10,25	10,00	10,25	3,75	7,00
V-lijak po SIST EN 12350-9:2010	VF	po 15 min	(s)	n.d.	6,45	4,90	4,03	3,72	5,37	4,69
	VF_{5min}	po 20 min	(s)	n.d.	7,56	5,41	4,46	4,00	5,72	5,41
razlez s posedom po SIST EN 12350-8:2019	SF	po 45 min	(mm)	n.d.	690/665	650/640	570/570	640/620	655/655	680/670
	VS	po 45 min	(s)	n.d.	2,28	1,21	1,67	1,28	1,34	1,42
prostorninska masa po SIST EN 12350-6:2019	ρ	po 5 min	(kg/m^3)	2375	2362	2360	2362	2369	2349	2355
opomba				segregira in krvavi	brez segregacije in naknadnega izločanja vode (krvavenja)					

Preglednica 6(b): Rezultati preiskav svežih mešanic polnilnega betona (SCC) - za sestave od 8. do 14. (od B-6 do A-2)

vrsta preskusa svežega polnilnega betona (SCC)	merjena lastnost	čas po zamešanju	merska enota	zaporedna številka sestave						
				8	9	10	11	12	13	14
				oznaka sestave						
				B-6	B-7	B-8	B-9	B-9-MP1	B-10	A-2
				15.10.2025	16.10.2025	22.10.2025	22.10.2025	30.10.2025	3.11.2025	6.11.2025
temperatura svežega betona	T_b	po 5 min	(°C)	17,2	n.d.	16,3	17,4	15,9	16,3	13,2
temperatura zraka	T_z	po 5 min	(°C)	14,8	n.d.	15,2	16,5	15,1	15,8	11,2
vodovezivno razmerje po SIST 1026:2016,NC	$(v/v)_{tot}$	po 5 min	(-)	0,481	0,486	0,488	0,490	0,501	0,477	0,502
vsebnost zraka po SIST EN 12350-7:2019, tč.5	A_1	po 5 min	(% v/v)	1,4	1,4	1,6	1,2	1,2	1,3	1,8
J-obroč po SIST EN 12350-12:2010	SFJ	po 10 min	(mm)	705/700	670/660	700/710	700/690	670/650	680/715	680/640
	t_{500J}	po 10 min	(s)	1,15	1,68	1,77	1,72	2,05	1,72	1,97
	PJ	po 10 min	(mm)	7,00	9,00	7,75	6,75	10,25	5,75	13,00
V-lijak po SIST EN 12350-9:2010	VF	po 15 min	(s)	4,71	5,07	4,38	4,47	4,93	4,83	4,88
	VF_{5min}	po 20 min	(s)	4,58	5,60	4,97	4,74	5,15	5,03	5,32
razlez s posedom po SIST EN 12350-8:2019	SF	po 45 min	(mm)	685/630	700/690	695/685	700/730	655/640	700/710	740/690
	VS	po 45 min	(s)	1,81	1,63	2,0	1,28	1,37	2,13	1,34
prostorninska masa po SIST EN 12350-6:2019	ρ	po 5 min	(kg/m^3)	2371	2380	2369	2371	2373	2384	2337
opomba				brez segregacije in naknadnega izločanja vode (krvavenja)						

5. PRIKAZ IN DISKUSIJA REZULTATOV PREISKAV SVEŽIH MEŠANIC SCC

Rezultate preiskav svežih mešanic polnilnega betona, oziroma samozgoščevalnega betona (SCC) podajamo v preglednici 6(a): za sestave od 1. do 7. (od B do B-5) in v preglednici 6(b): za sestave od 7. do 14. (od B-6 do A-2).

Kriteriji za posamezne lastnosti:

- porozimetrski indeks – $A_1 \leq 2{,}0$ %v/v,
- razprostiranje – SFJ = 700 ± 50 mm,
- razprostiranje – SF = 700 ± 50 mm,
- čas razprostiranja – $t_{500J} > 2$ s,
- čas razprostiranja – VS (t_{500}) > 2 s,
- sposobnost prehoda – PJ < 10 mm,
- čas tečenja (viskoznost) – VF < 9 s,
- čas tečenja (viskoznost) – $VF_{5min} < 12$ s.

Izmerjene totalna vodovezivna razmerja $(v/v)_{tot}$ vseh sestav so nekoliko manjša od projektirane vrednosti $(v/v)_{tot,proj}$ = 0,51. Pri tem izračunu je vezivna komponenta privzeta kot vsota količine cementa in suhega dela suspenzije mikrosilike v 1 m^3 vgrajenega betona. Na koncu mešanja nam je vedno ostala manjša količina vode.

Vsebnost zraka, oziroma porozimetrski indeks A_1 je pri vseh sestavah manjši od zahtevane vrednosti 2,0 %v/v, razen pri sestavi B-2 le malo presega zahtevano vrednost A_1 = 2,2 %v/v, kar pa je še sprejemljivo.

Oboji rezultati meritev razprostiranja SFJ_{10} (slika 3(a)) in SF_{45} (slika 3(b)) so v mejah zahtevanih vrednosti 700 ± 50 mm pri večini sestav (B-2, B-4, B-5, B-6, B-7, B-8, B-9 in B-10), kar je razvidno tudi iz slike 4, v kateri so prikazane povprečne vrednosti SFJ_{10} in SF_{45}.

Po naših izkušnjah je ocena viskoznosti s časom razprostiranja ($t_{500J,10}$ in VS $(t_{500})_{45}$) manj zanesljiva od ocene viskoznosti s časi tečenja (VF in VF_{5min}). Iz slike 5 je razvidno, da je večina rezultatov meritev časa razprostiranja manjša od zahtevanega kriterija 2 s.

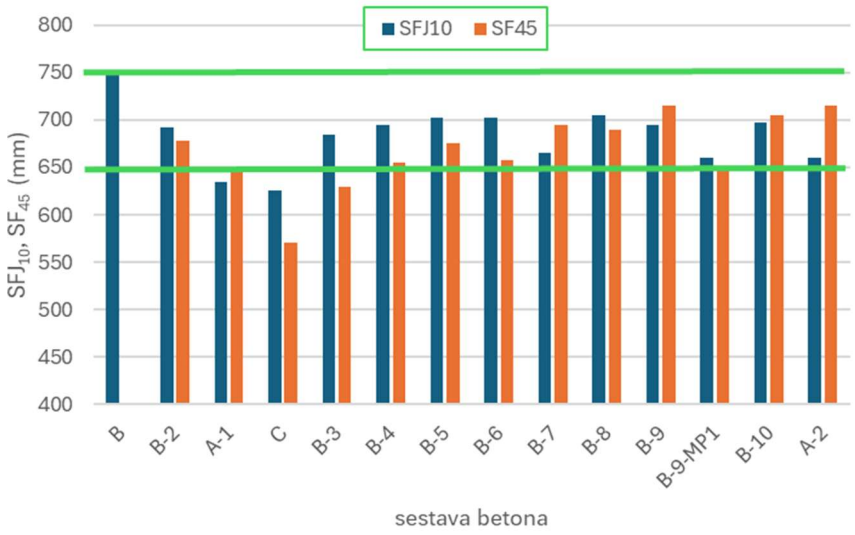
Nasprotno oceno viskoznosti pa lahko podamo, ko jo ocenjujemo s časi tečenja VF in VF_{5min}, ki smo ju merili pri preskusu z V-lijakom (slika 6). Vsi rezultati so dosti manjši od zahtevanih največjih časov tečenja: VF_{max} = 9 s in $VF_{5min,max}$ = 12 s (slika 7). Po 5 min so časi tečenja VF_{5min} le nekoliko večji od VF. Kljub temu, da so časi tečenja relativno kratki (SCC izkazuje nizka viskoznost) so SCC kompaktni, ne segregirajo in ne krvavijo, kar je možno videti v slikah 3(a) in (b).

Obstaja dobra korelacija med VF in VF_{5min} (slika 8). Glede na stalno vizualno ocenjevanje vsake mešanice lahko privzamemo to oceno viskoznosti kot primerno.



(a) (b)

Slika 3: Meritev razprostiranja: (a) SFJ_{10} pri preskusu z J-obročem po 10 min od priprave SCC; (b) SF_{45} pri preskusu razleza s posedom po 45 min od priprave SCC.



Slika 4: Povprečni rezultati meritve razprostiranja SFJ_{10} in SF_{45}.

Kljub nizki viskoznosti so polnilni betoni (SCC) kompaktni, nesegragabilni in ne krvavijo (sliki 3(a) in (b)).

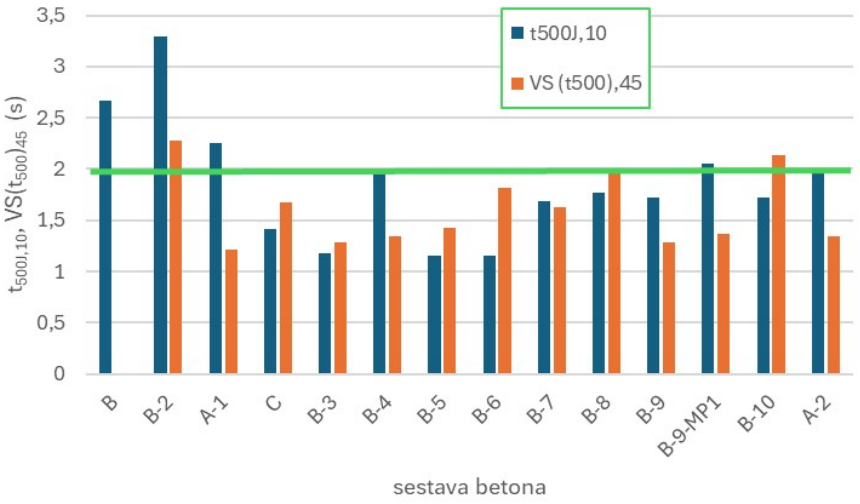
Sposobnost prehoda PJ smo merili pri preskusu z J-obročem (slika 9). Rezultati meritve so razvidni iz slike 10. Od 13 sestav polnilnega betona (SCC) jih 6 sestav ne izkazuje sposobnost prehoda.

Med pripravo in preiskavami svežega polnilnega betona, oziroma samozgoščevalnega betona (SCC) smo vizualno ocenjevali segregabilnost in krvavenje (naknadno izločanje vode). Samo pri prvi sestavi (B) smo zaradi prevelike količine superplastifikatorja zaznali precej veliko segregacijo in naknadno izločanje vode tako, da smo prenehali preiskave na tem SCC. Pri vseh ostalih SCC ni prišlo do segregacije in krvavenja.

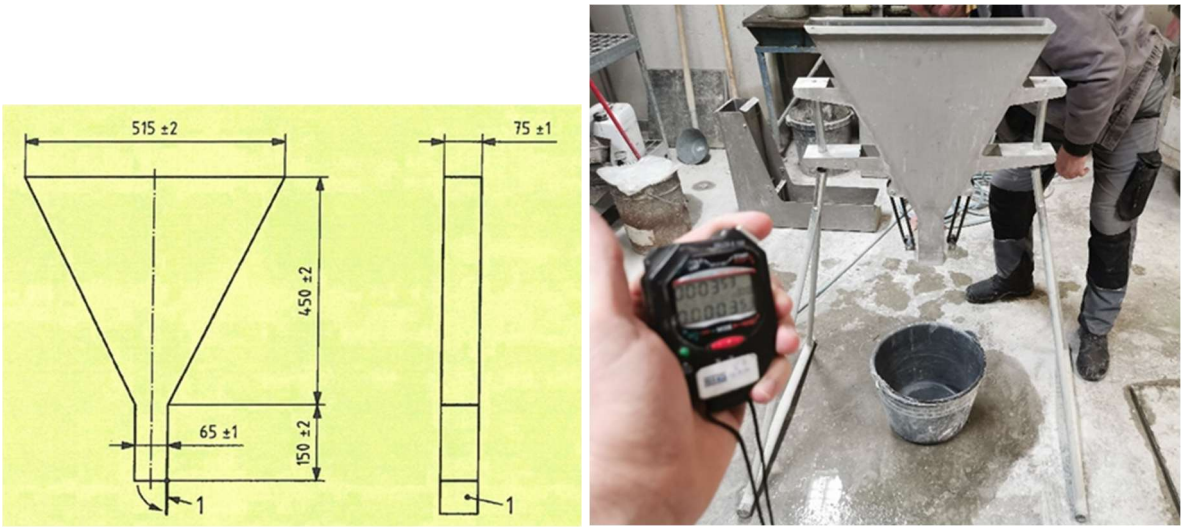
6. SKLEP

Na osnovi dobljenih rezultatov preiskovanih svežih mešanic polnilnega betona (PB), oziroma samozgoščevalnega betona (SCC) lahko sklepamo, da jih večina izkazuje primerno obdelovalnost, ki je potrebna za namensko uporabo – zapolnjevanje medprostorov med zabojniki v odlagalnem jašku. Sedem od trinajstih preiskanih mešanic izkazujejo tudi sposobnost prehoda, kar pomeni, da so sposobni dobro zapolniti tudi okolico robov zabojnikov.

Dobro razviden je vpliv relativno malih sprememb v sestavi SCC na njegovo obnašanje v svežem stanju, predvsem na njegovo odelovalnost (pretočnost, prehajanje in viskoznost). Poleg zamenjave ene ali dveh komponent sestave, izkazuje vpliv tudi sprememba skupne sestave agregata. Rezultati tudi potrjujejo našo odločitev, da se za dobro odelovalnost SCC uporabi prodnati agregat. Izboljšanje kompaktnosti svežega



Slika 5: Rezultati meritev časa razprostiranja t_{500J} in VS (t_{500}).

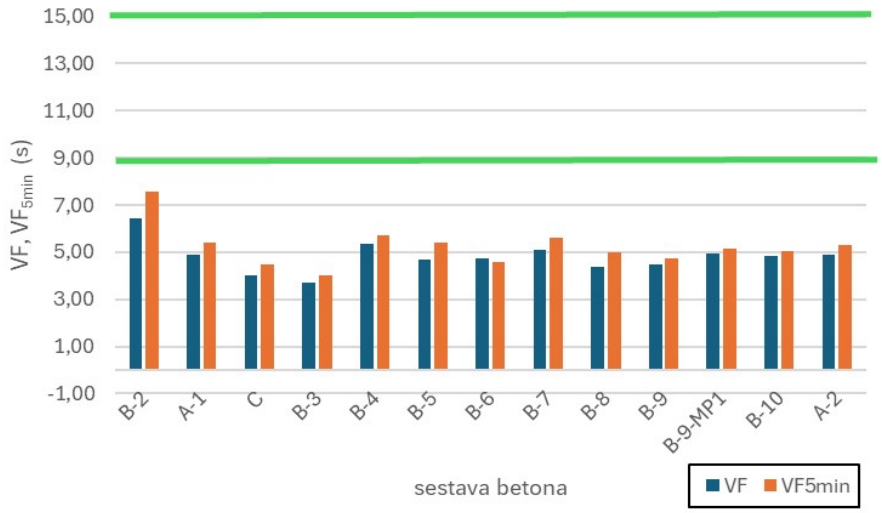


Slika 6: (a) skica V lijaka iz standarda SIST EN 1350-9:2010; oznaka 1: drsna loputa ali loputa na tečajih; (b) izvedba preskusa z V-lijakom.

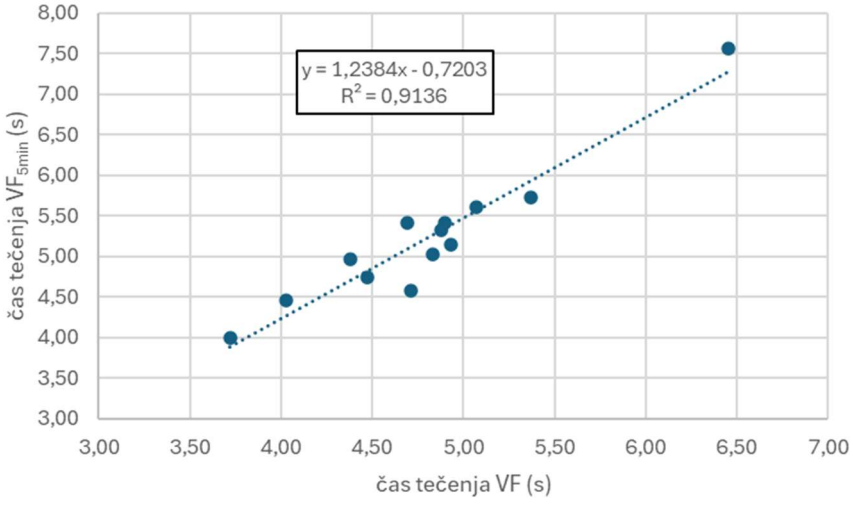
SCC smo dosegli z dodajanjem drobljene frakcije prodnatega agregata 0-2 mm, ki pa ne vpliva na njegovo obdelovalnost.

ZAHVALA

Avtorji se zahvaljujejo ARAO za financiranje RR projekta Študije proizvodnje, vgradljivosti in karakteristik končnih betonskih mešanic kot polnil med odlagalnimi zabojniki N2d v silosu odlagališča NSRAO.



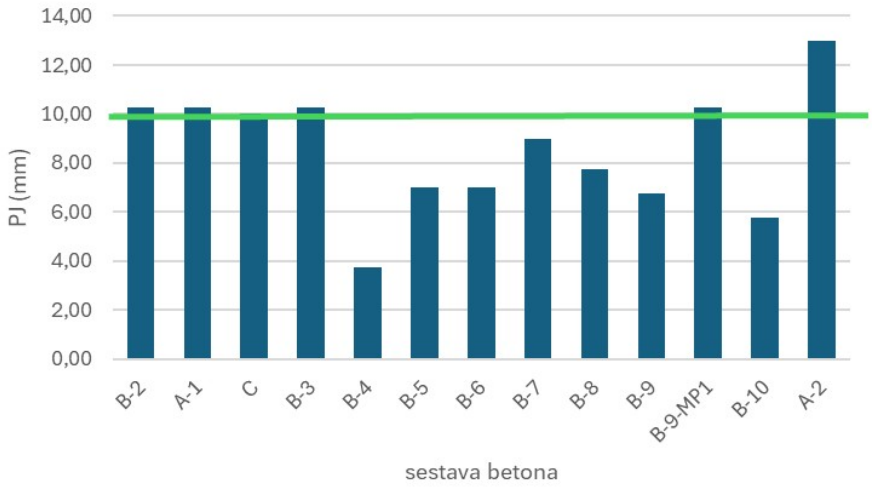
Slika 7: Rezultati časa tečenja VF in VF_{5min}.



Slika 8: Korelacija med časoma tečenja VF in VF_{5min}.



Slika 9: Meritev sposobnosti prehoda PJ pri preskusu z J-obročem.



Slika 10: Rezultati meritve sposobnosti prehoda PJ.

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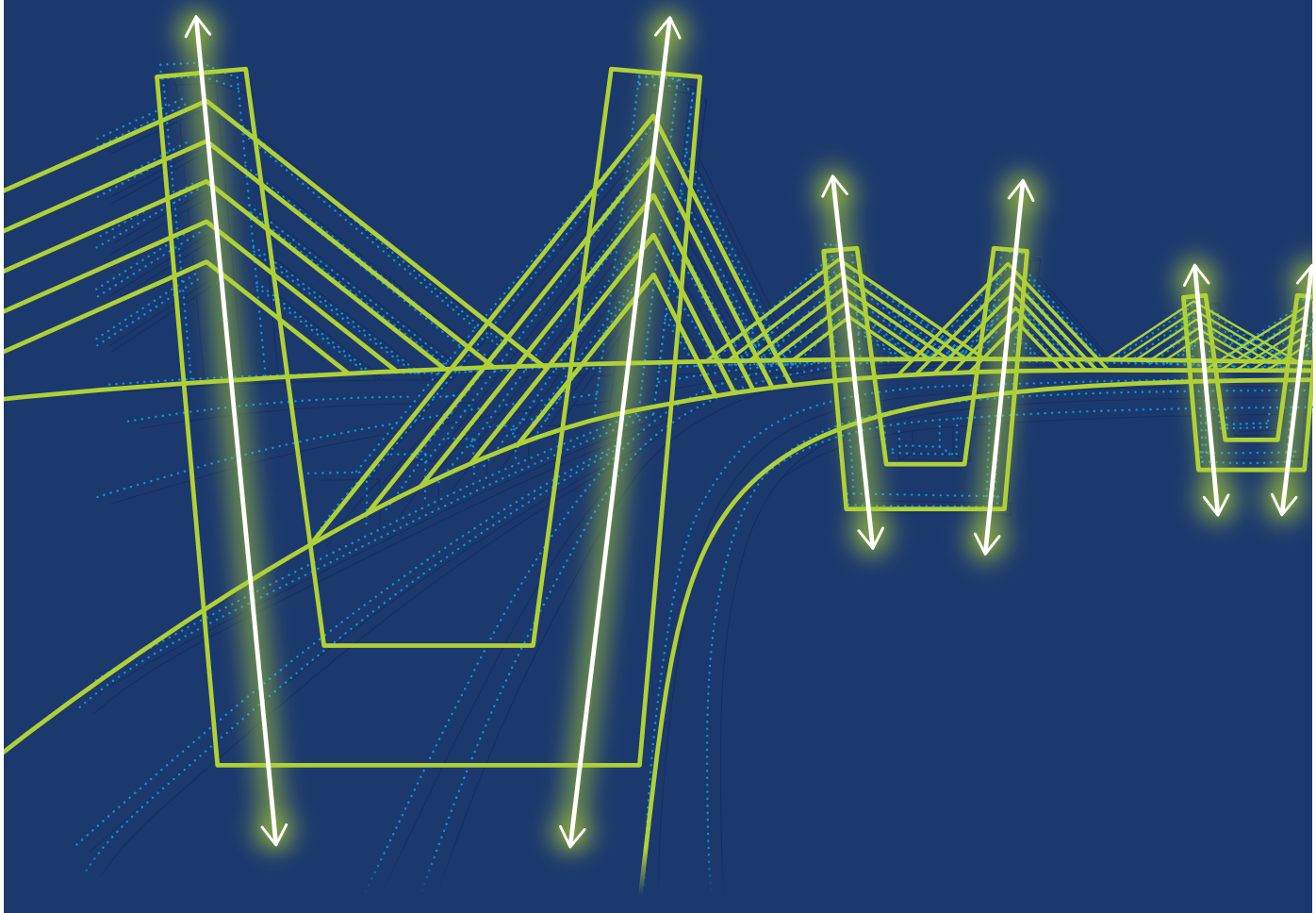
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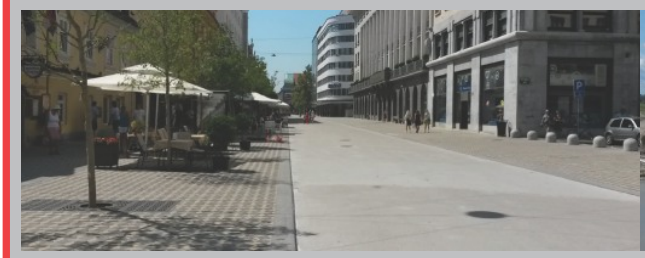
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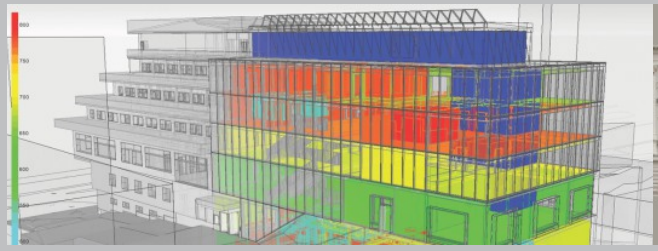
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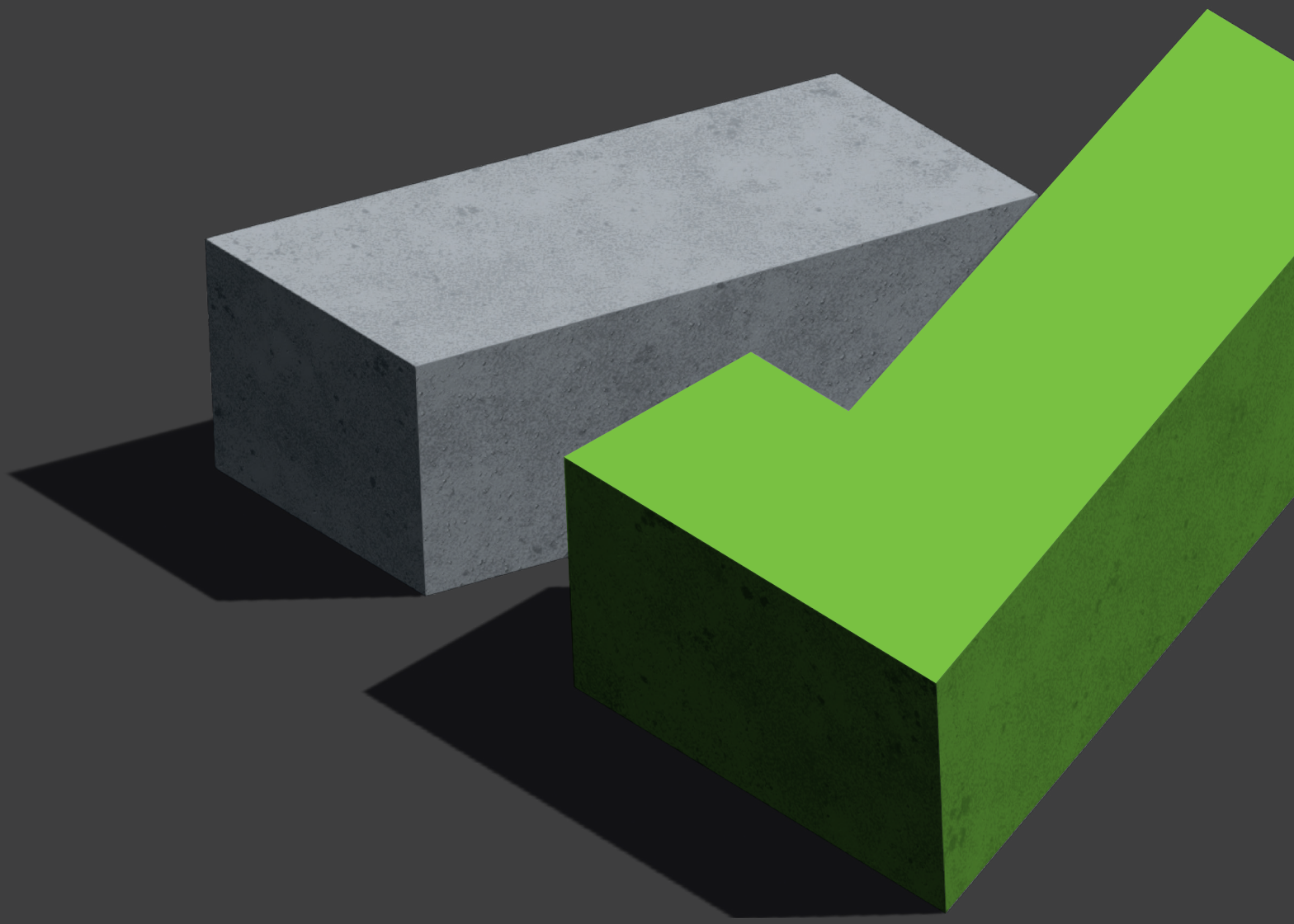
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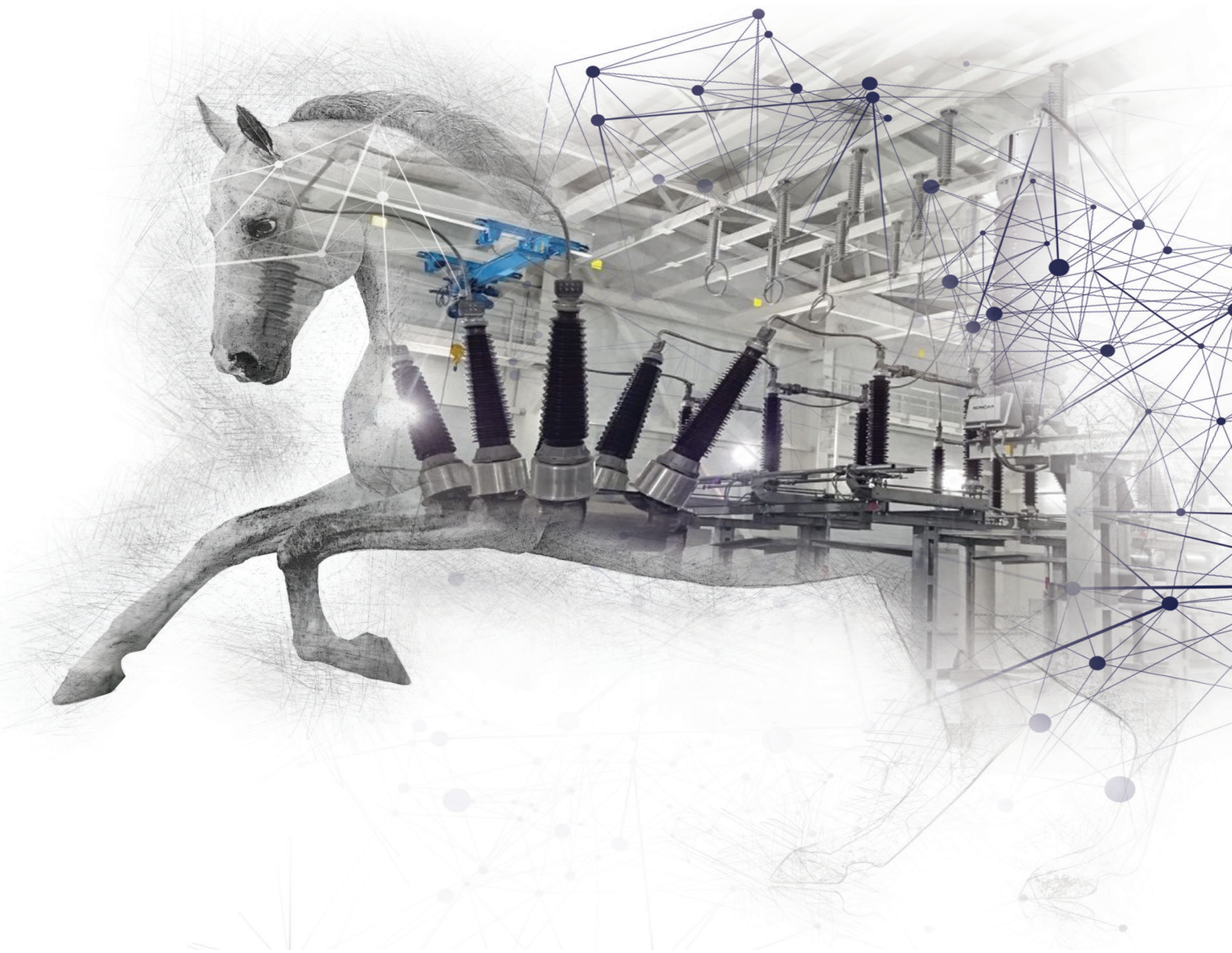
- kompleksen inženiring projektov (faza priprave in faza izvedbe investicije)
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