OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

Olivera BUKVIĆ
Vlastimir RADONJANIN
Mirjana MALEŠEV
Mirjana LABAN

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1 UVOD

Trodimenzionalno štampanje (3D štampanje) ili aditivna proizvodnja u opštem smislu predstavlja sukcesivno dodavanje slojeva materijala kako bi se formirao željeni model iz 3D digitalnog geometrijskog modela. Važno je napomenuti da se, iako postoje različite vrste aditivnih tehnologija (deponovanje istopljenog filameta, vezivna 3D štampa, stereolitografija, selektivno lasersko sinterovanje itd.), vrste materijala (materijali u čvrstom, tečnom, gasovitom stanju, praškasti materijali, laminati) i primene (za izradu prototipova ili proizvodnju), izraz 3D štampanje koristi kao opšti termin za sve aditivne tehnološke procese. Drugi termini koji su takođe u upotrebi jesu digitalna fabrikacija, tehnologija brze izrade prototipa ili CAD dizajn [27].

Proces 3D štampanja sastoji se od kreiranja 3D modela u computer-aided-design (CAD) formatu i njegovom eksportovanju u stereolitografski (STL) format,

1 INTRODUCTION

Three - dimensional printing (3D printing) or additive manufacturing is in general defined as successive assembling of the material layers in order to make objects or structures from a 3D data model. It is important to notice that, although there are several types of additive technologies (material extrusion, binder jetting, vat photo polymerization, powder bed fusion, etc.), materials used (i.e. materials in solid, liquid, gas state, powders or sheets) and application (for making of prototypes or for production), the term 3D printing is usually used as an umbrella term for all additive manufacturing processes. Other terms used as a synonym for additive manufacturing are digital fabrication, rapid prototyping or computer-aided design [27].

The process of 3D printing consists of creating the 3D model in computer-aided-design (CAD) format and exporting it to stereo lithography (STL) format with a specific

Olivera Bukvić, Asistent-master, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, olivera.bukvic@uns.ac.rs

Vlastimir Radonjanin, Redovni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, radonjanin.vlastimir@gmail.com

Mirjana Malešev, Redovni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, miram@uns.ac.rs

Mirjana Laban, Vanredni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, mlaban@uns.ac.rs

Olivera Bukvic, MSc, teaching assistant, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, olivera.bukvic@uns.ac.rs

Vlastimir Radonjanin, PhD, full professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, radonv@uns.ac.rs

Mirjana Malesev, PhD, full professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, miram@uns.ac.rs

Mirjana Laban, PhD, associate professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, mlaban@uns.ac.rs

pomoću specijalizovanog softvera. Digitalni format se zatim konvertuje u listu komandi koje treba da izvrši 3D štampač. Tip 3D štampača i njegova priprema za štampanje zavise od odabrane tehnologije štampanja [27].

Prema Američkom udruženju za testiranje i materijale (engl. American Society for Testing and Materials), postoji sedam kategorija aditivnih tehnoloških procesa: ubrizgavanje vezivnog sredstva, direktno energetsko taloženje, ekstrudiranje materijala, ubrizgavanje materijala, sjedinjavanje praha, laminacija listova i fotopolimerizacija [7].

Dve najviše istraživane i razvijane aditivne tehnologije za 3D štampanje betona jesu proces ekstrudiranja i ubrizgavanje vezivnog sredstva [27,42]. Ekstrudiranje materijala se zasniva na istiskivanju materijala kroz diznu, pravljenjem višeslojnih modela, bez upotrebe oplata [27]. Zbog prirode procesa, armatura se ne primenjuje, iako je pokušano da se armatura inkorporira u 3D štampanje betona procesom ekstrudiranja [1,2,35]. U okviru štampanja betona procesom ekstrudiranja, vremenom su razvijene dve tehnologije: Contour Crafting („izrada kontura“) i štampanje betona [27,42]. Contour Crafting (slika 1b) podrazumeva istiskivanje maltera, ili drugih materijala koji imaju vezivna svojstva, u slojevima, uz mistriju koja omogućava završnu obradu površine materijala, čineći je glatkom [12,17]. Štampanje betona je takođe proces ekstrudiranja, ali s manjom rezolucijom deponovanja i tri ose kretanja štampača (slika 1c) [16,17]. Tehnika ekstrudiranja koristi se za izvođenje konstrukcija „in-situ“, dok je 3D štampanje na praškastoj podlozi (tj. ubrizgavanje vezivnog sredstva) pogodno za primenu u pre-fabrikaciji konstruktivnih elemenata. Ova tehnologija štampanja je bazirana na selektivnom ubrizgavanju veziva u podlogu od praškastog materijala, čime se formira željeni 3D oblik očvršćavanjem materijala, na mestima gde je ciljano ubrizgano vezivo [42]. Proces je razvijen na principu aditivne proizvodnje polimera i metala, prilagođene betonu – praškasta podloga može biti agregat u koji se ubrizgava cementna pasta visokoplastične konzistencije, ili vezivo na bazi cementa ili geopolimera, u koje se ubrizgava [27]. Ova tehnologija aditivne proizvodnje koja se primenjuje u građevinarstvu poznata je i kao D-shape proces štampanja betona (slika 1a) [4,27].

Materijali koji se koriste u procesu ekstrudiranja

Sastav betona za 3D štampanje ekstrudiranjem i konvencionalnih cementnih betona značajno se razlikuju. Beton za 3D štampanje sadrži veću količinu Portland cementa i posledično manju količinu agregata. Takođe, da bi se postiglo štampanje betona, krupan agregat se izostavlja iz ovog kompozita. Najčešće korišćena nominalna maksimalna veličina zrna agregata u literaturi je 1–2 mm [13,20,24,25,33,37,40,41] ali su objavljena i eksperimentalna istraživanja s nominalnom maksimalnom veličinom i do 4,75 mm [1,3,5,36]. Ipak, postoje i nedavne studije o uticaju krupnog agregata (maksimalna veličina 10 mm) na osnovna svojstva 3D betona u svežem stanju [32]. Krupan agregat je korišćen i za izgradnju kuće pomoću specifičnog masivnog 3D štampača za proces ekstrudiranja [35].

Nezaobilazne komponente 3D štampanih betona jesu dodaci reduktori vode, ubrizivači i obično modifikatori viskoznosti [11,39]. Mešavine 3D štampanih betona sadrže i leteći pepeo, silikatnu prašinu i nano-glinu, kako

software. The digital model is then converted to a list of commands for 3D printer to conduct. The type of 3D printer and its preparation for printing depends on chosen printing technology [27].

According to the American Society for Testing and Materials, there are seven categories of additive manufacturing technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo polymerization [7].

The two most researched and developed additive manufacturing technologies used for 3D printing of concrete are material extrusion and binder jetting [27,42]. Material extrusion is based on selective dispensing of the material through a nozzle, making a multi-layer objects, with no need for formwork use [27]. Given the nature process, reinforcement is not used, although there have been attempts to incorporate it in extrusion-based 3D printing [1,2,35]. Under the extrusion-based concrete printing, two technologies have been eventually developed: Contour Crafting and concrete printing [27,42]. Contour Crafting (Figure 1b) is based on extrusion of a mortar or cementitious materials in layers, against a trowel which forms the smooth surface of the printed object [12,17]. Concrete printing is extrusion process as well, but with smaller deposition resolution and retained 3-dimensional freedom (Figure 1c) [16,17]. The extrusion-based processes are used for "in-situ" construction, while powder based 3D concrete printing (i.e. binder jetting) is suitable for making a precast structure elements. This printing technology is based on selective deposition of a liquid binder into a powder bed, creating the 3D object at the targeted areas where the powder is bound [42]. Powder-based 3D concrete printing is developed on the basis of methods for polymers and metals additive manufacturing, adjusted to concrete – powder bed can be made of aggregate in which a fluid cement paste is jetted, or the powder bed can be a cement-based or geopolymer-based binder in which the water is jetted [27]. This additive manufacturing technology applied in construction is also known as „D-shape“ process (Figure 1a) [4,27].

Materials used for extrusion based process

The compositions of concrete for extrusion-based 3D printing and conventional cement concrete are significantly different. Concrete for 3D printing has larger amount of Portland cement and consequently, smaller amount of aggregate. In addition, to achieve printability of concrete, the coarse aggregate is omitted from this composite. The most commonly found nominal maximum aggregate size in literature is 1-2mm [13,20,24,25,33,37,40,41], but nominal maximum sizes up to 4,75 mm is reported in experimental research as well [1,3,5,36]. However, there has been a recent study on the impact of coarse aggregate (maximum size 10mm) on basic 3D concrete fresh-state properties [32]. Coarse aggregate has been used for constructing a house with specific huge 3D extrusion-based printer [35].

The inevitable component of 3D printing concretes are water reducing admixtures, accelerators and, usually, viscosity modifying agents [11,39]. 3D printing concrete mixtures also contain fly ash, silica fume and nanoclay, to

Slika 1. Tehnologije 3D štampanja: D-shape (a), Contour Crafting (b) i 3D štampanje betona (c) [44]
Figure 1. 3D printing technologies: "D-shape" (a), Contour Crafting (b) and 3D concrete printing (c) [44]

bi se poboljšale performanse mešavina za štampu. Izazovi u projektovanju sastava 3D betonskih mešavina na koje treba odgovoriti jesu uspostavljanje veze između reoloških i tehnoloških svojstava s mogućnosti štampanja 3D betona i smanjenje ranog skupljanja usled sušenja, koje se javlja usled odsustva oplata i velikih količina cementa – više od 500 kg/m^3 , zbog čega je uobičajena primena polipropilenskih vlakana pri projektovanju mešavina [11,19,29,33,34,37,38]. Prema nekim istraživanjima, Portland cement je, za sada, najpouzdanije vezivo u pogledu postizanja zahtevanih svojstava 3D betona [11,29]. Međutim, velike količine cementa koje se koriste imaju negativan uticaj na okolinu, povećavaju eksploataciju prirodnih sirovina i cenu 3D štampanja [8]. Kako bi se rešili ovi problemi, prethodna iskustva s betonima koji se ugrađuju na tradicionalan način, u pogledu primene recikliranog lakog agregata i materijala s vezivnim svojstvima kojima se može zameniti deo cementa [18,30,31] mogu biti prilagođena i primenjena na 3D štampane betone. Istražuje se primena lakih krupnih agregata [32] i alternativnih veziva, kako bi se postigla svojstva eko-betona i betona povoljnih po okolinu i potrebna svojstva za 3D štampanje betona (npr. alternativni materijali koji imaju vezivna svojstva i geopolimerna veziva) [23,25].

improve the performance of printing mixtures. The challenges of 3D concrete mix design that need to be addressed to are establishing relation between the rheological and technological properties with printability of 3D printed concrete and, early age drying shrinkage reduction, due to the absence of formwork and large quantities of cement - more than 500 kg/m^3 which is why polypropylene fibres are commonly used in mixture design [11,19,29,33,34,37,38]. According to some studies, Portland cement is, for now, the most reliable binder that can ensure achieving the required 3D concrete properties [11,29]. However, large amount of cement used has a negative impact on environment, enlarges consumption of natural raw materials and increases cost of 3D concrete printing [8]. In order to resolve these problems, the previous experience in using recycled lightweight aggregates and supplementary cementitious materials in traditionally casted concrete mixtures [18,30,31] can be adjusted and applied for 3D printed concretes. The use of lightweight coarse aggregate [32] and alternative binders are investigated, in order to meet the needs of an eco and environmental friendly concrete and required properties for 3D concrete printing (e.g. supplementary cementitious materials and geopolymer binder) [23,25].

Prvi zvaničan patent, kao pokušaj da se automatizuje proces betoniranja, patentirao je Tomas Edison (engl. Thomas Edison), 1917. godine. Proces se sastojao od sipanja betona s Portland cementom u jednodelan kalup od livenog gvožđa, pomoću pumpe i sistema creva, od vrha do dna kalupa. Oblik kalupa bi, nakon sklapanja njegovih delova, odgovarao obliku objekta (npr. kuće ili zgrade), praveći jedinstvenu konstrukciju nakon očvršćavanja betona. Zbog nemogućnosti savladavanja kompleksnosti svojstava sveže betonske mešavine, kao i visoke cene opisanog kalupa, patent je primenjen samo nekoliko puta [2,6,39,47].

Značajan razvoj automatizacije izvođenja betonskih konstrukcija, nastavlja se 1990-ih godina. U prvoj polovini ove decenije, automatizacija se ogledala u procesu sklapanja prefabrikovanih elemenata, primenom specijalizovanih robota [39]. Istraživanje mogućnosti primene aditivne proizvodnje u izvođenju betonskih konstrukcija počinje tehnologijom sjedinjavanja praha, gde je pionir u objavljivanju ovih istraživanja Džozef Penja (Joseph Pegna - Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, New York, USA), 1997. godine. 3D štampanje betona ekstrudiranjem, primenom Contour Crafting procesa, predstavljeno je 1998. godine, od strane profesora Beroka Košnevisa (Berokh Khoshnevis, University of Southern California). Godine 2004. Predstavljen je zid odštampan u razmeri 1:1, a ovaj proces 3D štampanja je dalje razvijan kao tehnologija građenja „in-situ“ [2,12,39].

Od tada, 3D štampanje betona istražuje se mnogo šire, naročito od 2012. godine. Slobodna forma građenja je od velikog interesa za arhitekte, omogućavajući im veću slobodu pri projektovanju. Korišćenje oplata i kalupa za tradicionalno betoniranje ograničava kreativni izraz arhitekata, s obzirom na to što je oplata kompleksne geometrije veoma skupa i izrada ovakve oplata nije racionalna. Procenjeno je da su troškovi oplata 35%–65% ukupne cene betonske konstrukcije, dok je višestruka upotreba oplata ograničena ili nije moguća [2]. Izvođenje betonskih konstrukcija bez oplata smanjilo bi troškove izvođenja, kao i količinu građevinskog otpada i povećalo nizak godišnji rast produktivnosti, karakterističan za građevinsku industriju [2,27,35].

Iako su istraživanja u oblasti 3D štampanja betona u ranoj fazi i i dalje se unapređuju, iako još uvek ne postoje standardizovane metode za projektovanje sastava mešavina i ispitivanje 3D štampanog betona, u svetu postoje impresivni primeri mogućnosti uspešne primene ove tehnologije. Neki od njih prikazani su na slikama u nastavku.

Cilj ovog rada jeste objašnjenje najbitnijih svojstava ekstrudiranog 3D štampanog betona, kako bi se naglasile specifičnosti ove relativno nove i obećavajuće tehnologije građenja. Iako je terminologija za osnovna svojstva 3D štampanih betonskih mešavina (npr. obradljivost, tiksotropija, granica tečenja) ista kao i za mešavine za tradicionalno betoniranje, postoje dodatni zahtevi i osobine koje nijansiraju osnovne i prave suštinsku razliku u projektovanju sastava mešavina 3D štampanog betona.

The first officially patented attempt to automatize concrete casting was made by Thomas Edison in 1917. The process consisted of single-pouring a Portland cement mixture into the single-piece mould made of cast iron, through a pump and a hose system, from the top to the bottom of the mould. The mould is supposed to be in shape of entire structure (e.g. a house or a building) after assembling, making an integral construction after hardening of the cement mixture. However, due to inability to overcome the complexity of concrete mixture properties and high cost of described mould, this patent was implemented only a few times [2,6,39,47].

Significant increase in automation of in-situ construction of concrete structures started in 1990s. In the first part of the decade, this reflected in Japanese automated assembling of prefabricated elements using specialized robots [39]. Research on possibilities of the additive manufacturing application in construction of concrete structures begun with powder bed fusion technology published by Joseph Pegna (Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, New York, USA) in 1997. Extrusion-based 3D concrete printing using Contour Crafting process was introduced in 1998 by Berokh Khoshnevis, Professor of Engineering at the University of Southern California. In 2004, the 1:1 scale printed wall was shown, and this 3D printing process further developed to large scale on-site construction technology [2,12,39].

Since then, 3D concrete printing has been researched more extensively, especially since 2012. The freeform construction is of great interest for architects, giving them more design freedom. The use of formwork and moulds for traditional concrete casting limits the creative expression of architects, since the complex geometry formwork is very expensive and irrational to make. Furthermore, it is estimated that formwork costs are 35%-65% of total concrete construction costs, while formwork has limited or no possibility for re-use [2]. Making concrete structures without formwork would decrease the construction cost as well as construction waste and increase the low annual growth in productivity common for construction industry [2,27,35].

Although the research in the field of 3D concrete printing is at its early stage and still improving and the standardized methods for 3D printed concrete mixtures design and testing still do not exist, there have been impressive examples world-wide of potential successful application of this technology. Some of them are illustrated in the following figures.

The aim of this paper is to explain the most important fresh properties of extrusion-based 3D printed concrete in order to emphasize specificities of this relatively new and promising construction technology. Although the terminology for basic properties of 3D printed concrete mixtures (e.g. workability, thixotropy, yield stress) is the same as for traditionally casted concrete mixtures, there are additional requirements and properties that give nuances to the basic ones, making the crucial difference in design of 3D printable concrete mixtures.

Slika 2. Petospratni stambeni kompleks kineske kompanije WinSun, 2015 (1100m²) [14]
Figure 2. A five-story residential complex by Chinese company WinSun, 2015 (1100m²) [14]

Slika 3. Hotel Suite, Filipini, 2015 (12.5x10.5x4.0m) [2]
Figure 3. Hotel Suite, Philippines, 2015 (12.5x10.5x4.0m) [2]

Slika 4. Stub proizveden od strane XtreeE kompanije [28]
Figure 4. Support column produced by XtreeE company [28]

Slika 5. The Y-Box Paviljon, "21st-century Cave" - Supermachine Studio i Siam Cement Group - 3 m visoka konstrukcija [35]
Figure 5. The Y-Box Pavilion, 21st-century Cave by Supermachine Studio and Siam Cement Group – 3m tall structure [35]

Slika 6. Prvi 3D štampani pešački most, "Institute of Advanced Architecture of Catalonia", 2017 (raspon – 12 m, širina – 1.75 m) [44]

Figure 6. The first 3D printed pedestrian bridge, by Institute of Advanced Architecture of Catalonia, 2017 (span – 12m, width – 1.75m) [44]

Primenjeni metod za prikupljanje podataka o svojstvima u svežem stanju uključuje pristup „odozdo na gore“. Pregledana je aktuelna literatura u oblasti 3D štampanja betona i proširena je pregledom referenci iz prvobitno uključene literature. Na osnovu kriterijuma za inkluziju, u pregled literature uključeni su pregledni i eksperimentalni radovi o 3D betonu štampanom procesom ekstrudiranja. Radovi koji se tiču isključivo svojstava očvrslag 3D štampanog betona nisu uzeti u obzir.

Method used for gathering data on fresh-state properties include bottom-up research approach. The recent literature in the field of 3D concrete printing was reviewed and was extended by reference screening of the included papers. Based on the inclusion criteria, a review and experimental papers about extrusion-based 3D concrete printing were included. Papers containing only hardened properties of 3D printed concrete were excluded.

2 OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

Termini u literaturi na engleskom jeziku koji se koriste za opis svojstava 3D štampanog betona u svežem stanju, uglavnom, jesu izvedenice glagola i često je prevod na srpski jezik otežan. Zbog toga je potrebno opisno definisati pojedina svojstva.

Svojstva 3D štampanog betona u svežem stanju su kompleksna, preklapaju se i veoma su zavisna od vremena. Mogu se podeliti na reološka (granica tečenja, plastična viskoznost i tiksotropija), tehnološka (pumpabilnost i sposobnost tečenja) i na svojstva koja određuju sposobnost štampanja (sposobnost ekstrudiranja, kvalitet štampe i buildability svojstvo). Sposobnost štampanja 3D betona (engl. printability) najvažnije je svojstvo za proces 3D štampe. Nije striktno definisano, ali se odnosi na svojstva u svežem stanju koja je potrebno postići kako bi

2 BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

Fresh-state properties of 3D printed concrete are complex, overlapping and highly time-dependent. They can be divided into rheological (yield stress, plastic viscosity and thixotropy), technological properties (pumpability and flowability) and printability properties (extrudability, print quality and buildability). The printability of the 3D concrete is the most important property for 3D printing process. It is not strictly defined, but it refers to fresh-state properties needed to successfully conduct the printing process, from extrusion to the end of the process [39].

Since there are no standardized methods and procedure for defining and evaluating these complex 3D concrete properties, the terminology found in the body of

se sprovelo štampanje, od ekstrudiranja do kraja procesa [39].

Kako ne postoje standardne metode i procedure za definisanje i ocenu ovih kompleksnih svojstava 3D betona, terminologija u literaturi nije uvek konzistentna, u smislu objedinjavanja ili jasnog razdvajanja određenih svojstava.

Pumpabilnost (engl. pumpability ili deliverability) jeste sposobnost betonske mešavine da se transportuje od mešalice, kroz cev, do dizne. Povezana je s plastičnom viskoznošću i granicom tečenja betonske mešavine (tj. reološkim svojstvima), kao i sa snagom pumpe i tehnologijom pumpanja mešavine, koje moraju biti odabrane u skladu s reološkim svojstvima [27]. Složenost pumpanja 3D betonske mešavine ogleda se u vremenski zavisnim svojstvima betona u svežem stanju, pojavi „krvarenja” betona i segregacije. Dovoljna količina cementne paste neophodna je kako bi se formirao sloj oko čestica agregata, smanjilo trenje, a time smanjio i napon smicanja između njih. Ovim dolazi do porasta obradljivosti 3D mešavine u smislu pumpabilnosti/transporta kroz sistem za pumpanje [37]. U jednom istraživanju opsega u kome se kreće sposobnost štampanja, odnosno, printability svojstvo 3D štampanog betona [37], autori uvode indeks pumpabilnosti kako bi kvantifikovali pumpabilnost mešavine za štampu. Kako bi se dobili rezultati, za svaku probnu mešavinu, indeks pumpabilnosti je računat kao odnos brzina tečenja mešavine i tečenja vode (ml/s), za konstantnu brzinu pumpanja, u odabranom vremenskom intervalu. Veće vrednosti indeksa pumpabilnosti ukazuju na lakše pumpanje mešavine [37].

Sposobnost tečenja (engl. flowability) predstavlja lakoću s kojom beton teče pod određenim uslovima i uglavnom se ispituje metodom rasprostiranja [19]. Uticaj optimalne količine agregata na sposobnost tečenja ispitivali su Zhang i dr. [43].

Sposobnost ekstrudiranja ili ekstrudabilnost (engl. extrudability) definiše se kao sposobnost betonske mešavine da bude kontinualno istiskivana kroz diznu štampača [19,33]. Različiti tipovi dizni prikazani su na slikama 7 i 8. S porastom sposobnosti tečenja, raste i sposobnost

literature is sometimes not fully consistent, in terms of joining or separating properties one from another.

Pumpability (or deliverability) is the ability of concrete mixture to be transported from mixer, through a hose, to a nozzle. It is related to plastic viscosity and yield stress of the concrete mixture (i.e. rheology properties) and power of the pump as well as its technology must be chosen in accordance with them [27]. The challenges of pumping 3D concrete mixtures reflect in the time-dependent fresh-state properties, bleeding and segregation. The sufficient amount of cement paste is necessary so it could form a coat around aggregate particles and reduce the friction between them and reduce the shear stress. This will lead to increase of the 3D mixture workability in terms of pumpability/in terms of transporting through the pumping system [37]. In the study on printability region for 3D printed concrete [37], authors introduce the pumpability index to quantify the pumpability of the printing mixture. For each trial mixture, pumpability index is calculated as ratio of the mixture flow rate and water flow rate (ml/s) for constant pumping speed, in a selected time interval, to obtain the results. Higher pumpability index indicates easier mixture pumping [37].

Flowability is the ease with which concrete flows under given conditions, and is usually tested by the slump flow test [19]. The impact of an optimum aggregate content on flowability is investigated by Zhang et al. [43].

Extrudability is defined as ability of the printing mixture to be continuously extruded out of the printer nozzle [19,33]. Different nozzle types are shown at the Figure 8 and Figure 9. With the increase of flowability, extrudability increases as well. Therefore, extrudability depends on the quantity of dry constituents/components in the concrete mixture, properties of the used materials, delivery system (i.e. printer/printer nozzle), water content, conditions during printing, etc. However, the mixture proportions will have the biggest impact, which is why several authors recommend, as a guideline, to design the initial printing mixtures with properties similar to the self-compacting concretes [19,39].

Slika 7. Kružna dizna [2]
Figure 7. Round nozzle [2]

Slika 8. Kvadratna dizna s bočnim mistrijama [45]
Figure 8. Squared nozzle with side trowels [45]

ekstrudiranja. Zbog toga će značajan uticaj na ovo svojstvo imati sadržaj suvih komponenti u betonskoj mešavini, svojstva komponentnih materijala, sistem za dovodjenje mešavine (tj. štampač/dizna štampača) sadržaj vode, trenutni uslovi prilikom štampanja, i tako dalje. Najveći uticaj će ipak imati odnos komponentnih materijala, zbog čega neki autori predlažu, kao smernicu, projektovanje sastava betonskih mešavina sa svojstvima sličnim svojstvima samougrađujućeg betona [19,39].

Sposobnost ekstrudiranja može biti narušena usled isušivanja vode i segregacije – slično kao kod toka pumpanja, iako je ekstrudiranje proces s manjim brzinama protoka [39]. Pumpabilnost i sposobnost ekstrudiranja takođe su slične zbog smicanja mešavina tokom procesa, iako se, tokom ekstrudiranja, mešavina smiče u dizni, pod različitim uslovima u odnosu na smicanje u cevi prilikom pumpanja [34]. Sposobnost ekstrudiranja štampanog betona ispituje se vizuelno, najčešće na sloju ekstrudiranom u unapred definisanom vremenskom intervalu. Ne postoje preporuke za pouzdanije metode ispitivanja sposobnosti ekstrudiranja [15,33]. Prema nekim autorima, može biti procenjena preko svojstava kvaliteta štampanja [33], koja su objašnjena u narednom paragrafu.

Kvalitet štampanja (engl. *print quality*) u literaturi se odnosi na tri zahteva u pogledu štampane mešavine. Prvi je kvalitet površine odštampanog sloja (engl. *surface quality*) koja treba da bude bez defekata, odnosno diskontinuiteta. Odvajanje delova slojeva (slika 9) često je opisano u različitim istraživanjima, a pojavljuje se usled prekomerne krutosti i slabe kohezije mešavine za štampanje – loše obradljivosti. Sledeći zahtev za kvalitet štampanja jeste da ivice moraju biti pravougaone (engl. *squared edges*), što podrazumeva da ivice nanetog sloja moraju biti izražene. Izraz „pravougaone ivice” predložili su naučnici koji su istraživanje sprovedi na štampaču s diznama kvadratnog oblika, ali se izraz odnosi na konzistentnost oblika nanetog sloja u odnosu na oblik dizne [11].

Extrudability can be compromised by water drainage and phase separation – similar as with pumping flow, although extrusion is a process with slower flow velocities [39]. In addition, pumpability and extrudability are similar due to shearing of the mixture, although during extrusion, the mixture is sheared in the nozzle, under different condition than shearing in the pipes during pumping [34]. It is examined visually, usually on the layer extruded in predefined time period. There has been no recommendations for more reliable extrudability testing method [15,33]. According to some authors, extrudability can be assessed through the print quality properties [33], which are explained in the following paragraph.

Print quality in the literature refers to three printing mixture requirements. The first one is surface quality of the deposited layers, which has to be free of defects, i.e. discontinuities. The tearing of the layers (Figure 9) is often reported in different studies and it appears due to the excessive stiffness and low cohesion of the printing mixture – poor workability. Next requirement for the print quality is squared edges, which means that the edges of the deposited layer must be visible. The term squared edges is proposed by the researchers that conducted studies using squared printer nozzles, but it refers to the consistency of the deposited layer's shape with the shape of the nozzle, in general/regardless of the nozzle type [11].

Slika 9. Kvalitet površine – odvajanje odštampanog sloja usled slabe kohezije i prekomerne krutosti mešavine za štampanje [10]

Figure 9. Surface quality – tearing of the printed layer due to low cohesion and excessive stiffness of the printing mixture [10]

Treći zahtev je dimenziona usaglašenost i konzistentnost dimenzija. Da bi ovaj kriterijum bio ispunjen, potrebno je definisati prihvatljiv raspon dimenzija sloja. Ukoliko su dimenzije odštampanog sloja u okviru predviđenog raspona, dimenziona usaglašenost je postignuta. Dimenziona usaglašenost se odnosi na sposobnost mešavine da bude odštampana u slojevima s prihvatljivim rasponom ciljanih dimenzija. Konzistentnost dimenzija odnosi se na variranje širine odštampanog sloja. U studiji o svojstvima mešavine za štampanje u svežem stanju, Kazemian i dr. objavili su da variranje prethodno definisane širine sloja do 10% daje prihvatljiv kvalitet štampanja. Ova variranja odnose se samo na sloj u svežem stanju, odmah nakon deponovanja i ne uzimaju u obzir promene u dimenzijama usled skupljanja betona [10,11]. Dimenziona usaglašenost ispitivana u Kazemian i dr. eksperimentu prikazana je na slici 10, a rezultati merenja konzistentnosti dimenzija na slici 11. Svojstva kvaliteta štampanja ispituju se vizuelno i preporučeno je da se podešavaju kroz više proba s nekoliko ponovljenih mešavina, jer ne postoje predložene metode za ispitivanje i ocenu ovih svojstava [7].

The third requirement is dimension conformity and dimension consistency. For fulfilling this requirement, the acceptable range of the layer dimensions must be defined. If the dimensions of the printed layer are within the range, the dimension conformity is achieved. The dimension conformity is the ability of printing mixture to be printed as layers with acceptable range of targeted dimensions. The dimension consistency refers to variations in printed width of a single layer. In the study on fresh-state printing mixture properties, Kazemian et al. reported that 10% variation of the pre defined layer width is acceptable printing quality. These variations only refer to fresh concrete layer, right after its deposition and do not consider the dimensional changes caused by concrete shrinkage [10,11]. Dimension conformity investigated in Kazemian et al. experiment is shown in Figure 10, and results of measuring dimensional consistency on Figure 11. Print quality properties are examined visually and it is recommended to tune them through several trials with several mixture replicates, since there are no suggested methods for testing and evaluating these properties [7].

Slika 10. Dimenziona usaglašenost odštampanih slojeva [10]
Figure 10. Dimension conformity of the printed layers [10]

Slika 11. Konzistentnost dimenzija – variranje širine odštampanog sloja [10]
Figure 11. Dimension consistency - variations in width of the printed layer [10]

Svojstvo *printability window* se u literaturi definiše kao „vremenski period tokom kog mešavina za štampanje može biti ekstrudirana s prihvatljivim kvalitetom, kroz diznu, razmatrajući gubitak obradljivosti tokom vremena”. Ovo svojstvo se naziva i otvoreno vreme za rad (engl. *open time*) i može se meriti metodom rasprostiranja kako bi se procenio gubitak obradljivosti preko sposobnosti tečenja [19]. Imajući u vidu tehnologiju 3D štampanja, neki autori predlažu definisanje dva parametra povezana sa ovim svojstvom: najkraće vreme nakon kog kvalitet štampanja počinje da opada, usled gubitka obradljivosti (engl. *printability limit*) i najkraće vreme nakon kog mešavina za štampanje ne može biti ekstrudirana kroz diznu, odnosno blokada dizne usled procesa očvršćavanja betona (engl. *blockage limit*). Primećeno je da blokada dizne usled očvršćavanja može nastupiti mnogo pre početnog vremena vezivanja betona. Stoga je preporučeno da se vreme za koje mešavina može biti ekstrudirana ispita za svaku mešavinu, tokom projektovanja sastava. Ovo ukazuje na to da gubitak obradljivosti i početak vremena vezivanja ne mogu biti pouzdana zamena za direktno merenje ovih parametara. Dodatni izazov u uspostavljanju veze između obradljivosti i svojstva *printability window* i predlaganju adekvatnih metoda ispitivanja jeste zavisnost vremena nakon kog kvalitet štampanja počinje da opada i vremena nakon kog mešavina za štampanje ne može biti ekstrudirana od svojstava štampanja tj. mehanizma ekstrudiranja [11].

Svojstvo *buildability* (sposobnost deponovanja slojeva jedan na drugi) predstavlja sposobnost odštampnog betonskog sloja da prihvati opterećenje i sposobnost da se odupre deformacijama tokom štampanja u slojevima [9,11,19,24]. Usko je povezano i može se smatrati istim svojstvom kao i stabilnost oblika (engl. *shape stability*, *shape retention* ili *green strength*) jer oba svojstva zavise od brzine strukturiranja (porasta granice tečenja s vremenom), a kriterijum za ocenu ovog svojstva se u eksperimentalnim istraživanjima često zasniva na ranoj čvrstoći (engl. *green strength*) [9,11,39]. Stabilnost oblika može biti definisana kao sposobnost deponovanog sloja da zadrži konzistentan oblik dizne [25], dok se svojstvo *buildability* uglavnom izražava brojem slojeva sukcesivno štampanih jedan na drugi [19]. Deformacije odštampnih slojeva mogu nastati usled sopstvene težine, težine narednih slojeva i pritiska ekstrudiranja. Zadovoljavajući kvalitet štampe mešavine (engl. *print quality*) ukazuje na to da će odštampni sloj moći da se odupre deformacijama uzrokovanim sopstvenom težinom, dok otpornost na ostale vrste deformacija mora biti potvrđena laboratorijskim ispitivanjem tokom projektovanja sastava mešavine [11]. Naponi pritiska u donjim slojevima, indukovani sopstvenom težinom i težinom narednih slojeva, rastu tokom sukcesivnog deponovanja slojeva. Kada ovaj napon pređe granicu tečenja materijala, dolazi do obrušavanja odštampnih slojeva. Osnovni parametri koji određuju svojstvo *buildability* jesu granica tečenja, plastična viskoznost i tiksotropija. Usled procesa očvršćavanja, *buildability* svojstvo odštampne mešavine će rasti vremenom, zajedno s granicom tečenja materijala i modulom elastičnosti [39]. Napon smicanja kojem je izložena mešavina koja se štampa tokom procesa pumpanja i ekstrudiranja indukuje tiksotropiju mešavine. Unutršnja struktura betona će se narušavati i izgrađivati, utičući na viskoznost i, posledično, na stabilnost oblika [11]. Stoga će brzina štampanja modela zavistiti od brzine

Printability window is defined in literature as “the period of time during which the printing mixture could be extruded by the nozzle with acceptable quality, considering the workability loss that occurs over time”. This property is also referred to as an “open time” and can be measured using the slump flow test in order to assess the workability loss by flowability [19]. Considering the technology of 3D printing, some authors suggest defining two parameters related to the printability window: printability limit and blockage limit. The printability limit is the earliest time when print quality starts to decrease due to workability loss. The blockage limit is the earliest time when the printing mixture cannot be extruded out of the nozzle, due to its hardening. It is noted that blockage could occur long before the initial time setting of concrete. Therefore, it is recommended to test blockage limit during mixture design, for each mixture. Furthermore, this indicates that workability loss and setting time cannot be reliable alternatives for direct measuring of printability window parameters. Additional challenge for establishing the relationship between workability and printability window and proposing adequate testing methods is the dependency of printability limit and blockage limit on the printer properties, i.e. extrusion mechanism [11].

Buildability is the load carrying capacity of printed concrete layer and its ability to resist deformations during the layer wise printing [9,11,19,24]. It is closely linked to and can be considered to be almost the same property as shape stability (shape retention or green strength) since both depend on structuration rate (i.e. yield stress increase with time), and buildability criteria is often based on the green strength in experimental research [9,11,39]. Shape stability can be defined as the ability of the deposited layer to retain its shape consistent with the nozzle shape [25], while buildability is usually expressed through the number of layers that can be successively deposited [19]. The deformation of printed layers can occur due to self-weight, weight of the next layers and extrusion pressure. Satisfactory printing quality of the mixture indicates that the printed layers will resist self-weight deformations, while the resistance to other two deformation types must be confirmed with laboratory testing during the mix design [11]. The compressive stress induced by self-weight and weight of other layers in bottom layers increase during successive layer deposition. When this stress becomes higher than yield stress of the material, the failure occurs. The main parameters that determine buildability are yield stress, plastic viscosity and thixotropy. Buildability of the printing mixture increases with time, along with the material yield stress and elastic modulus, due to the hardening process [39]. The shear stress applied to the printing mixture during the pumping and extrusion induces the thixotropic behaviour of the mixture. Therefore, internal concrete's structure will break-down and build-up, influencing on viscosity and consequently, on the shape stability [11]. Hence, the building rate of the printed model depends on the structuration rate/structural build-up (i.e. yield stress increase with time), but also on nozzle velocity and length and thickness of the printed layers [11,29]. This means that structuration rate could be considered as a printing process dependent parameter, to account the variability of the mentioned printing properties, which imposes additional complexity to this material requirement [39]. Initial material yield stress and structuration rate are

strukturiranja (porasta granice tečenja s vremenom), ali i od brzine dizne i dužine i debljine sloja koji se štampa [11,29]. To znači da se brzina strukturiranja može smatrati parametrom koji zavisi od procesa štampanja, kako bi se uzele u obzir varijacije navedenih karakteristika štampača, što doprinosi dodatnoj složenosti zahteva u pogledu ovog svojstva [39]. Početna granica tečenja i brzina strukturiranja jesu najbitnija reološka svojstva koja se suprotstavljaju naponima pritiska u slojevima, indukovanim gravitacionim opterećenjem [34]. Čak i ako napon ne premašuje napon na granici tečenja, usled kumulativnog napona u slojevima, može doći do pojave značajnih deformacija i narušavanja geometrije odštampanih slojeva. Dodatno, vitki vertikalni štampani modeli izloženi su izvijanju nakon određenog broja odštampanih slojeva modela, zbog čega štampani beton mora, relativno rano, razviti visoke vrednosti modula elastičnosti. Dokazano je da, s porastom visine odštampanog modela, napon tečenja potreban za savladavanje napona pritiska raste linearno, dok modul elastičnosti potreban za odupiranje izvijanju raste sa eksponentom 3. Kao posledica navedenog, do određene visine štampanog elementa (odnosno broja odštampanih slojeva), kritično za svojstvo *buildability* biće obrušavanje usled napona pritiska u donjim slojevima, uzrokovanog težinom viših slojeva. Nakon te visine, najveći uticaj na *buildability* svojstvo štampanog betona će imati izvijanje [39]. Iako se svi naučnici slažu da su neophodna dalja istraživanja i dodatni eksperimentalni rezultati za bolje razumevanje mehanizma formiranja stabilnosti oblika, pokazano je da primena nano-gline u mešavinama doprinosi porastu brzine strukturiranja u periodu mirovanja (engl. *struc-turation at rest*) betonske mešavine za štampanje [11,22,23,46].

Slika 12 prikazuje analizu *buildability* svojstva u eksperimentalnom istraživanju koje su sproveli Panda i dr. Pored broja deponovanih slojeva pre pojave plastičnih deformacija (odnosno obrušavanja), elastične deformacije slojeva ispitane su na kontrolnoj mešavini i na mešavini modifikovanoj glinom, koja je pokazala bolje *buildability* svojstvo [22]. Slika 13 pokazuje posledice veze između *buildability* svojstva i pumpabilnosti, sposobnosti tečenja i stabilnosti oblika prikazanih u Tay i dr. [37].

Kao kvantitativni parametar za stabilnost oblika, Panda i dr. koriste faktor stabilnosti oblika, izračunat kao odnos poprečnog preseka ekstrudiranog materijala i poprečnog preseka dizne [26]. Prema eksperimentalnim istraživanjima, napon na granici tečenja raste linearno tokom perioda mirovanja, uzrokujući linearan porast stabilnosti oblika s vremenom. Stabilnost oblika utiče na očvrsla svojstva štampanog betona, preko povezanosti s vremenskim razmakom štampanja između sukcesivnih slojeva (engl. *printing time gap*). Kraći vremenski razmak uzrokuje jaču mehaničku vezu dva odštampana sloja nakon očvršćavanja i obrnuto. Ipak, štampanje u kratkom vremenskom razmaku izvodljivo je samo za mešavine s visokom stabilnosti oblika, jer odštampani sloj mora imati sposobnost da izdrži težinu narednih slojeva odmah nakon ekstrudiranja. Dalje, vremenski razmak štampanja će zavisiti od rastojanja koje prelazi dizna tokom štampanja sloja (tj. dužine sloja) i brzine štampanja [11]. Ovo naglašava složenost i zavisnost više svojstava štampanih betona u svežem i očvrsлом stanju od karakteristika štampača.

rheological properties of the highest importance for withstanding the gravity-induced compressive stresses in single and multiple layers [34]. Even if this stress does not exceed the yield stress, significant deformation can occur, due to the cumulative stress in layers, and it can impact the geometry of the printed layers. Additionally, slender vertical printed models are exposed to the buckling, after a certain number of printed layers/model height is achieved, which is why printing concrete must develop high elastic modulus relatively early. It is proven that, with the height increase of the printed object, yield stress needed to resist compressive stress increases linearly, while the elastic modulus needed to resist the buckling increases with the power of 3 of the printed object height. This means that below certain object height (number of printed layers) compressive stress failure will be critical for the buildability. Above this height, the buckling will have most impact on the buildability of the printing concrete [39]. Although all researchers agree that the further research and experimental data is needed for better understanding the mechanisms of forming the shape stability, the use of nanoclay in mixtures is reported to increase the build-up or "structuration at rest" of the printing mixtures [11,22,23,46].

Figure 12 shows the buildability analysis in the experimental study by Panda et al. Besides the number of deposited layers before plastic deformation (i.e. collapsing), elastic deformation of layers is examined on the control mixture and clay modified mixture, which showed higher buildability [22]. Figure 13 shows the consequences of the relations between buildability and pumpability, flowability and shape retention, presented by Tay et al. [37].

As a quantitative parameter for shape stability, Panda et al. use shape retention factor, calculated as ratio between cross section area of extrudate and cross section area of the nozzle [26]. According to the experimental research, yield stress increases linearly during the dormant period, causing linear increase of shape stability with time. The shape stability impacts the hardened properties of printed concrete through the linkage with printing time gap between successive layers. The shorter printing time gap will result in higher mechanical bond between layers and vice versa. However, printing with short time gaps can be feasible only if the mixture has high shape stability, meaning that the printed layer must be capable of withstanding the weight of the following layer right after extrusion. Furthermore, printing time gap will depend on nozzle travelling distance during layer printing (i.e. the layer length) and printing speed [11]. This emphasizes the complexity and dependence of multiple fresh and hardened printing concrete properties and printer properties.

Slika 12. Laboratorijsko ispitivanje "buildability" svojstva odštampane mešavine, opisano preko broja deponovanih slojeva pre obrušavanja [22]

Figure 12. Laboratory testing of buildability of the printing mixtures describe through number of deposited layers before the structure collapsed [22]

Imajući na umu navedeno, većina naučnika predlaže kombinovano ispitivanje stabilnosti oblika. Kazemian i dr. procenjivali su stabilnost oblika preko sleganja slojeva i ispitivanja cilindrom, za vremenski razmak štampanja slojeva od 0 i 19 minuta. Sleganje slojeva ispitano je na dva odštampana sloja, jedan preko drugog, i merenjem sleganja analizom fotografija u program za obradu fotografija. Ispitivanje za vremenski razmak od 19 minuta pokazalo je da nema deformacija u donjem sloju za mešavinu s dodatkom silikatne prašine, polipropilenskih vlakana i nano-gline, dok je prosečna vrednost deformacija za pet merenja na mešavinama s Portland cementom bila 1,5 mm [11]. Ovo ispitivanje prikazano je na slici 14, a uzorak od pet sukcesivnih slojeva prikazan je na slici 15.

Having in mind all the above, a vast majority of the researches propose combined testing of the shape stability. Kazemian et al. assessed shape stability with layer settlement and cylinder stability test, for zero and 19 minutes time gap. Layer settlement test was performed by printing two layers on top of each other and measuring settlement by analyzing photos with image processing program. The test for 19 minutes time gap showed there were no deformations of the bottom layer for mixtures with silica fume, polypropylene fibres and nanoclay, while the average deformation for 5 measuring of Portland cement mixture was 1.5mm [11]. This test is shown at Figure 14, while five layer specimen is shown at Figure 15.

Slika 13. Maksimalan broj odštampanih slojeva – "buildability" svojstvo u zavisnosti od pumpabilnosti, sleganja i sleganje rasprostiranjem: mešavine a-c imaju nizak indeks pumpabilnosti, visoku stabilnost oblika, male vrednosti sleganja i sleganja rasprostiranjem, dok mešavine d-f imaju viši indeks pumpabilnosti, nisku stabilnost oblika i veće vrednosti sleganja i sleganja rasprostiranjem [37]

Figure 13. Maximum number of layers printed - buildability, depending on pumpability, slump and slump flow: mixtures a-c have low pumpability index, high shape retention and low slump and slump-flow values, while mixtures d-f have higher pumpability index, low shape retention and higher slump and slump flow values [37]

Slika 14. Ispitivanje sleganja slojeva – obrušavanje prilikom vremenskog razmaka u štampanju od 0 minuta (gore) i 19 minuta (dole) [10]

Figure 14. Layer settlement test – collapse with zero time gap (top) and 19 minute time gap (bottom) [10]

Slika 15. Stabilnost oblika sukcesivno odštampanih slojeva s vremenskim razmakom od 19 min [10]

Figure 15. Shape stability of successively printed layers with interlayer time gap of 19 minutes [10]

Dodatno, u ovoj eksperimentalnoj studiji, stabilnost oblika merena je ispitivanjem na cilindričnim uzorcima, a slično su predložili i Perrot i dr. [10,29]. Kazemian i dr. predlažu nanošenje konstantnog opterećenja od 5.5 kg i merenje promene visine uzorka, Perrot i dr. su povećavali opterećenje u inkrementima od 1.5N, kako bi se dobio maksimalan napon pre pojave plastične deformacije [10,29]. Na primer, za vremenski razmak štampanja slojeva od 17 sekundi, prosečno vreme loma četiri uzorka bilo je 656 sekundi nakon nanošenja opterećenja, pri naponu od 4,76 kPa, prosečno. Za vremenski razmak od 60 sekundi, nije uočena plastična deformacija. [29]. Uzorci ispitani u Perrot i dr. za različite vremenske razmake štampanja prikazani su na slici 16 i slici 17.

Additionally, in this experimental study, shape stability was measured by cylinder stability test, while the similar was proposed by Perrot et al. [10,29]. While Kazemian et al. proposed imposing a constant load of 5.5kg and measuring the change in specimen height, Perrot et al. increased the load in 1.5N increments, in order to obtain the maximum stress before the plastic deformation [10,29]. For example, for 17 seconds printing time gap, the 4 specimens average failure time was 656 seconds after load imposing, at 4,76 kPa, average. For 60 second time gap, no plastic deformation was detected [29]. The specimens tested by Perrot et al. for different printing time gaps are shown at Figure 16 and Figure 17.

Slika 16. Pukotine usled plastične deformacije prilikom ispitivanja cilindričnog uzorka – vremenski razmak štampanja 17 s

Figure 16. Fractures on cylinder stability test specimen, due to plastic deformation – 17s time gap

Slika 17. Ispitivanje na cilindričnom uzorku – vremenski razmak štampanja 60 s

Figure 17. Cylinder stability test specimen – 60s time gap

3 ZAKLJUČAK

U ovom radu prikazana su osnovna svojstva ekstrudiranog 3D štampanog betona u svežem stanju – pumpabilnost, sposobnost tečenja (tehnološka svojstva), sposobnost ekstrudiranja, kvalitet štampanja i buildability svojstvo (svojstva koja određuju mogućnost štampanja). Analizirana svojstva su veoma vremenski zavisna i zavisna od karakteristika štampača. Njihove definicije često se preklapaju i njihova kompleksnost predstavlja izazov za pronalaženje opšteg rešenja i procedura za projektovanje sastava mešavine za štampanje zadovoljavajućih karakteristika.

Iako se oblast 3D štampanja betona obimno istražuje, rezultati daljih eksperimentalnih istraživanja potrebni su kako bi bili predloženi pouzdani modeli za uspostavljanje veze između tehnoloških i reoloških svojstava štampanih betona sa svojstvima koja određuju sposobnost štampanja. Teoretska znanja su i dalje potrebna da bi se moglo, kvantitativno i kvalitativno, izraziti koja su to željena svojstva betonske mešavine za 3D štampu. Specifičnost svojstava 3D štampanog betona u svežem stanju stvara potrebu za uspostavljanjem nove terminologije, u poređenju s terminologijom koja se odnosi na betone koji se ugrađuju na tradicionalan način. Jedno od osnovnih svojstava betona u svežem stanju, obradljivost (engl. workability) ne može biti definisana i opisana na isti način za 3D betone kao i za tradicionalne [11]. Obradljivost se smatra „sposobnošću betonske mešavine u svežem stanju za transport, ugradnju i doradivanje, bez pojave segregacije”, ili, preciznije „količinom korisnog unutrašnjeg rada ili energije koja je potrebna da se prevaziđe unutrašnje trenje između betona i oplate ili armature” [21]. Na primer, bitno svojstvo 3D štampanog betona jeste buildability, to jest njegova veza s brzinom strukturiranja koja je zavisna od vremena. Konzistencija i vreme vezivanja mešavine za štampanje mora biti u određenom intervalu, kako bi zadovoljila zahteve procesa ekstrudiranja, ali s druge strane, odštampani slojevi moraju razviti rane čvrstoće gotovo odmah nakon ekstrudiranja, kako bi prihvatili težinu narednih slojeva. Stoga uobičajena definicija obradljivosti

3 CONCLUSIONS

This paper presents the basic fresh-state properties of extrusion-based 3D printed concrete –pumpability, flowability (technological properties), extrudability, print quality and buildability (printability properties). All analyzed properties are highly time-dependent and printer-dependent as well. Their definitions are often overlapping and their complexity is challenging for finding general solutions and procedures for designing the printable mixtures with satisfying performance.

Although the field of 3D concrete printing is recently extensively researched, further experimental results are needed in order to propose reliable models for linking technological and rheological properties of printing concrete with printability properties. There is still a great need for theoretical knowledge to express, quantitatively and qualitatively, the desirable printing mixture properties. Specific fresh - state properties of 3D printing concretes required establishing the new terminology compared to the traditionally casted concretes. For example, one of the basic properties of the fresh concrete – workability – cannot be defined and described in the same way for 3D concrete as for traditional concrete [11]. Workability is considered as the ability of concrete to “be properly compacted and also transported, placed and finished sufficiently easily without segregation”, or, more strictly, as “the amount of useful internal work or energy required to overcome the internal friction between concrete and the formwork or reinforcement” [21]. For example, the important property of 3D concrete is buildability, i.e. its correlation with structuration rate, which is time dependent. The consistency and setting time of the printing mixture must be in certain interval to meet the needs of extrusion, but on the other hand, printed layers must obtain green strengths almost immediately after extruding, in order to bare the load of the following layers. Therefore, the usual definition of workability should be adjusted, since this term in 3D printing process combines a whole set of inter-dependable factors. It is recommended to evaluate the workability of 3D printing mixtures by investigating fresh-state concrete properties relevant

mora biti prilagođena, jer ovaj termin u procesu 3D štampanja obuhvata širok spektar međuzavisnih faktora. Preporučeno je da se obradljivost 3D mešavina za štampanje ocenjuje ispitivanjem svojstava betona u svežem stanju koja su relevantna za 3D štampane betone – kvalitet štampe, stabilnost oblika i svojstvo printability window [11].

S obzirom na to što ne postoje standardizovane metode za ispitivanje i ocenu svojstva 3D štampanih betona, većina istraživanja se i dalje zasniva na eksperimentalnim probama (engl. trial-and-error). Zbog toga će svi rezultati istraživanja u oblasti 3D štampanih betona doprineti daljem razvoju i napretku ove tehnologije.

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for 3D printed concretes – print quality, shape stability and printability window [11].

Since there are no standardized methods for testing and evaluation of 3D printed concrete properties, most of the research is still based on trial-and-error experimental approach. That is why every research result in the field of 3D concrete printing contributes to further development and improvement of this technology.

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APSTRAKT

OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

*Olivera BUKVIĆ
Vlastimir RADONJANIN
Mirjana MALEŠEV
Mirjana LABAN*

Cilj ovog rada je pregled osnovnih svojstava trodimenzionalnog (3D) štampanog betona u svežem stanju, štampanog procesom ekstrudiranja, kako bi se objasnila specifična svojstva ove tehnologije građenja. Pregled je sproveden pristupom „odozdo na gore“. Kao polazna tačka, korišćena je aktuelna literatura u oblasti štampanja betona procesom ekstrudiranja, dok je, pregledom referenci relevantnih naučnih radova, odabrana dodatna literatura za pregled. Na osnovu kriterijuma za inkluziju, analizirani su pregledni i eksperimentalni radovi koji sadrže podatke o svojstvima 3D štampanog betona u svežem stanju, kao i oni koji sadrže podatke o materijalima korišćenim za 3D štampanje, s obzirom na to što njihova svojstva direktno utiču na svojstva betonske mešavine u svežem stanju. Radovi koji sadrže podatke samo o svojstvima betona u očvrslom stanju nisu uzeti u obzir. Svojstva koja su predmet pregleda jesu: tehnološka svojstva (pumpabilnost i sposobnost tečenja) i svojstva koja određuju sposobnost štampanja (engl. printability – sposobnost ekstrudiranja, kvalitet štampanja i svojstvo buildability).

Ključne reči: 3D štampanje, aditivna proizvodnja, svojstva betona u svežem stanju, proces ekstrudiranja, tehnološka svojstva, svojstva koja određuju sposobnost štampanja

ABSTRACT

BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

*Olivera BUKVIC
Vlastimir RADONJANIN
Mirjana MALESEV
Mirjana LABAN*

This paper aims at reviewing the basic properties of fresh-state extrusion-based three-dimensional (3D) printed concrete in order to explain the specific properties of this construction technology. The review was conducted using the bottom-up approach. The most recent literature in the field of extrusion-based concrete printing was used as a starting point, while additional papers were included through screening the references of relevant papers. Based on the inclusion criteria, review and experimental papers containing data on fresh-state 3D printed concrete properties were included, as well as materials used for 3D printing, since their properties directly affect the fresh-state properties of concrete mixture. Papers concerning data only on hardened properties were excluded. Reviewed properties are: technological properties (pump ability and flow ability) and printability properties (extrudability, print quality and buildability).

Key words: 3D printing, additive manufacturing, fresh-state properties, extrusion-based process, technological properties, printability properties