OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

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

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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,

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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].

Materijali koji se koriste u procesu ekstrudiranja

Sastav betona za 3D štampanje ekstrudiranjem i konvencionalnim cementnim betonima značajno se razlikuju. Beton za 3D štampu 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 do 4,75 mm [1,3,5,36]. Ipak, postoje i nedavnije 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].

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

100

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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 oplate 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 primenjena na 3D štampane betone. Istražuje se primena lakih krupnih agregata [32] i alternativnih veziva, kako bi se postigli 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 jednodelen 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 1950-ih godina. U prvoj polovini ove decenije, automatizacija se ogledala u procesu sklapanja prefabrikovanih elemenata, primenom specijalizovanih roboti [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 processa, predstavljeno je 1998. godine, od strane profesora Beroka Košnevisa (Berokh Koshnevis, University of Southern California). Godine 2004. Predstavljen je izd odstampač 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 oplate i kalupa za tradicionalno betoniranje ograničava kreativni izraz arhitekata, s obzirom na to što je opala kompleksne geometrije veoma skupa i izrada ovakve oplate nije racionalna. Procenjeno je da su troškovi oplate 35%–65% ukupne cene betonske konstrukcije, dok je višestruka upotreba oplate ograničena ili nije moguća [2]. Izvođenje betonskih konstrukcija bez oplate smanjilo bi troškove izvođenja, kao i količinu građevinskog otpada i povećalo nizak godišnji rast produktivnosti, karakterističan za građevinsku industriju [2,27,35].

Iako su istraživača u oblasti 3D štampanja betona u ranoj fazi 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 tećenja) 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.
Figure 2. A five-story residential complex by Chinese company WinSun, 2015 (1100m²) [14]

Figure 3. Hotel Suite, Philippines, 2015 (12.5x10.5x4.0m) [2]
Figure 4. Support column produced by XtreeE company [28]

Figure 5. The Y-Box Pavilion, “21st-century Cave” by Supermachine Studio and Siam Cement Group – 3m tall structure [35]
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 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 sa plasticnom viskoznošću i granicom tečenja betonske mešavine (tj. reološkim svojstvima), kao i sa snagom pumpe i tehno- logijom pumpanja mešavine, koje moraju biti odabrane u skladu s reološkim svojstvima [27]. Složenost pumpanja 3D betonske mešavine ogleda se u vremenskim zavisnim svojstvima betona u svežem stanju, pojavom "krvarenja" betona i segregacije. Dovoljna količina cementne paste je neophodna da 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 [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 brzine tečenja mešavine i tečenja vode (ml/s) za konstantnu brzinu pumpanja, u odabranom vremenskom intervalu. Veće vrednosti indeksa pumpabilnosti ukazuju na lakšu 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) definise se kao sposobnost betonske mešavine da bude kontinualno istiskivana kroz diznu štampača [19,33]. Različiti tipovi dizna prikazani su na slikama 7 i 8. S porastom sposobnosti tečenja raste i sposobnost pumpabilnosti, odnosno, transporta kroz sistem za pumpanje [37].

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].
ekstrudiranja. Zbog toga će značajan uticaj na ovo svojstvo imati sadržaj suvih komponenti u betonskoj mešavinu, svojstva komponentnih materijala, sistem za dovođenje 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 vizualno, najčešće na sloju ekstrudiranog 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. Sledeci 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 istraživali štampač sa diznom 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 održavanog sloja u okviru predviđenog raspona, dimenziona usaglašenost je postignuta. Dimenziona usaglašenost se odnosi na sposobnost mešavine da bude održavan u slojevima s prihvatljivim rasponom ciljanih dimenzija. Konzistentnost dimenzija odnosi se na variranje širine održavanog 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 vizualno 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 definisao 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 rasprostranjanja kako bi se procenio gubitak 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). Primijećeno 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 izazovi 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 štampača tj. mehanizma ekstrudiranja [11]. Svojstvo buildability (spособност deponovanja slojeva, jedan na drugi) predstavlja sposobnost oštaštanog 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 ekperimentalnim istraživanjima često zasniva na ranoj čvrstoći (engl. green strength) [9,11,39]. Stabilnost oblika može biti definiсana kao sposobnost deponovanog sloja da zadrži konzistentan oblik dizne [25], dok se svojstvo buildability uglavnom izražava brojem slojeva uspešno štampanih jedan na drugi [19]. Deformacije oštaštanih slojeva mogu nastati usled sopstvene težine, težine narednih slojeva i pritiska ekstrudiranja. Zadovoljavajući kvalitet štampa mešavine (engl. print quality) ukazuje na to da će oštaštani sloj moći da se odupre deformacijama uzrokovanim sopstvenom težinom, dok otpornost na ostale vrste deformacije mora biti potvrđena laboratorijskim ispitivanjem tokom projektovanja sastava mešavine [11]. Napon 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 obrašavanja oštaštanih slojeva. Osnovni parametri koji određuju svojstvo buildability jesu granica tečenja, plastična viskoznost i tiksotropija. Usled procesa očvršćavanja, buildability svojstvo oštaštanе mešavine će rasti vremenom, zajedno s granicom tečenja materijala i modulom elastičnosti [39]. Napon smicanja kojem je izložena mešavina koja se štampa tokom procesa pumpiranja i ekstrudiranja indukuje tiksotropiju mešavine. Unutrašnja struktura betona će se narušavati i izgradivati, utičući na viskoznost i, posledično, na stabilnost oblika [11]. Stoga će brzina štampanja modela zavisiti 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 tixotropy. 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 tixotropy 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

GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE 63 (2020) 4 (99-117) BUILDING MATERIALS AND STRUCTURES 63 (2020) 4 (99-117)
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 zavisiti od procesa štampanja, kako bi se uzele u obzir varijacije navedenih karakteristika štampača, što doprinosi dodatnoj složenosti zahteva u pogledu ovog svijeta [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 naponja 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 izvijanja raste sa eksponentom 3. Kao posledica navedenog, do određene visine štampačkog elementa (odnosno broja odštampanih slojeva), kritično za svojstvo buildability biće obračušavanje usled naponja pritiska u donjim slojevima, uzrokovanih tečinom viših slojeva. Nakon te visine, najveći uticaj na buildability svojstvo štampačkog betona će imati izvijanje [39]. Iako se svi naučnici slažu da su neophodna dalja istraživanja i dodatni eksperimentalni rezultati za bolje razumijevanje mehanizma formiranja stabilnosti oblika, pokazano je da primena nano-gline u mešavinama doprinosi porastu brzine strukturiranja u periodu mirovanja (engl. structuration at rest) betonske mešavine za štampačke [11,22,23,46].

Slika 12 prikazuje analizu buildability svojstva u eksperimentalnom istraživanju koje su sprovedli Panda i dr. Pored broja deponovanih slojeva pre pojave plastičnih deformacija (odnosno obračušavanja), elastične deformacije slojeva ispllane su na kontrolnoj mešavini i na mešavinu modificiranoj glinom, koju 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, izračunan 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 štampačkog betona, preko povezanosti s vremenskim razmaku, odvojeno u jedno slojevima i poprečnom preseku dizne [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]
Layer settlement test – collapse with zero time gap (top) and 19 minute time gap (bottom) [10]

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

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.
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 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.

Jako se oblast 3D štampanja betona obimno istražuje, rezultati daljih eksperimentalnih istraživanja potrebni su kako bi bili predočeni pouzdani modeli za uspostavljanje veze između tehničkih 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 betone [11]. Obradljivost se smatra „sposobnošću betonske mešavine u svežem stanju za transport, ugradnju i završnu obradu koje je moglo da se izraziti unutrašnje snage između betona i oplate ili armature” [21]. Na primer, bitno svojstvo 3D štampanog betona jeste buildability, to jest njegova sposobnost ekstrudiranja, a to je nezavisno od vremena. Konzistencija i vreme vezivanja mešavine za štampanje mora biti u određenom intervalu, kako bi zadovoljila zahteve procesa ekstrudiranja, ali i s druge strane, odštampani slojevi moraju razviti rane čvrstoće gotovo odmah nakon ekstrudiranja, kako bi pripisane 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 štampi, 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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APSTRAKT

OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU
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Mirjana MALEŠEV
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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, korишćena 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 korишćenim 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 odreдjuju 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
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Mirjana MALESEV
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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