PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM RAZLIČITIH FUNKCIJA ZRELOSTI BETONA: PRIMER IZ PRAKSE

ASSESMENT OF CONCRETE COMPRESSIVE STRENGTH USING DIFFERENT MATURITY FUNCTIONS: CASE STUDY

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1 UVOD

Čvrstoća pri pritisku jeste svojstvo betona, najvažnije prilikom projektovanja i izvočenja konstrukcija. Često se ostala svojstva – poput čvrstoće pri zatezanju, modula elastičnosti i trajnosti – povezuju s čvrstoćom pri pritisku betona. U naučnoj i stručnoj zajednici, najviše se poklanjala pažnja modelovanju razvoja čvrstoće pri pritisku betona tokom vremena. Većina modela uključuje u razmatranje više parametara od kojih su najznačajniji oni koji se odnose na svež beton, kao što su vrsta i količina pojedinih komponentnih materijala. Ipak, na razvoj čvrstoće betona veliki uticaj ima i temperatura, koja se uglavnom ne razmatra, jer je većina modela zasnovana na ispitivanjima u laboratoriji pri nekoj konstantnoj temperaturi.

Kada je beton u pitanju, neophodno je razdvojiti uticaj temperature kao uslova sredine odnosno nege betona od temperature koja je posledica hidratacije cementa. Posledice delovanja povišene temperature umnogome se razlikuju u zavisnosti od mesta nastanka. Ovo je posebno bitno u slučaju masivnih betona, gde se povećana temperatura usled hidratacije cementa ne može zanemariti.

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1 NTRODUCTION

Compressive strength is a property of concrete of the highest importance throughout design and construction stage. Other properties, such as tensile strength, modulus of elasticity and durability are often associated with concrete compressive strength. Consequently, scientific and practitioners' communities pay most attention to the development of models for this particular concrete property. Most of these developed models take into account two or more parameters among which the parameters related to fresh concrete such as type and quantity of component materials are the most significant. In addition, temperature has great influence on the development of concrete strength. However, this parameter is almost never taken into consideration since most models are based on laboratory tests performed at a constant temperature.

When it comes to concrete, it is necessary to separate the impact of temperature as an environmental condition, i.e., concrete curing condition, and temperature generated by cement's hydration. Consequences of elevated temperature differ substantially depending on the place of origin. This is especially important in the case of massive concrete elements, in which temperature increases since the hydration of cement cannot be ignored.

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Kontrola čvrstoće betona u konstrukciji, prema američkim propisima, podeljena je prema vrstama i veličini konstrukcije. Propisane su metode koje se primenjuju za pločaste elemente do 300 mm debljine, kao i više metoda za sve ostale tipove i veličine konstrukcija. Najčešće primenjivane metode jesu otpornost na utiskivanje, *pullout* i metode na bazi zrelosti betona. Za svaki od navedenih pristupa, standardom su propisane metode ispitivanja i izračunavanja čvrstoće betona u konstrukciji.

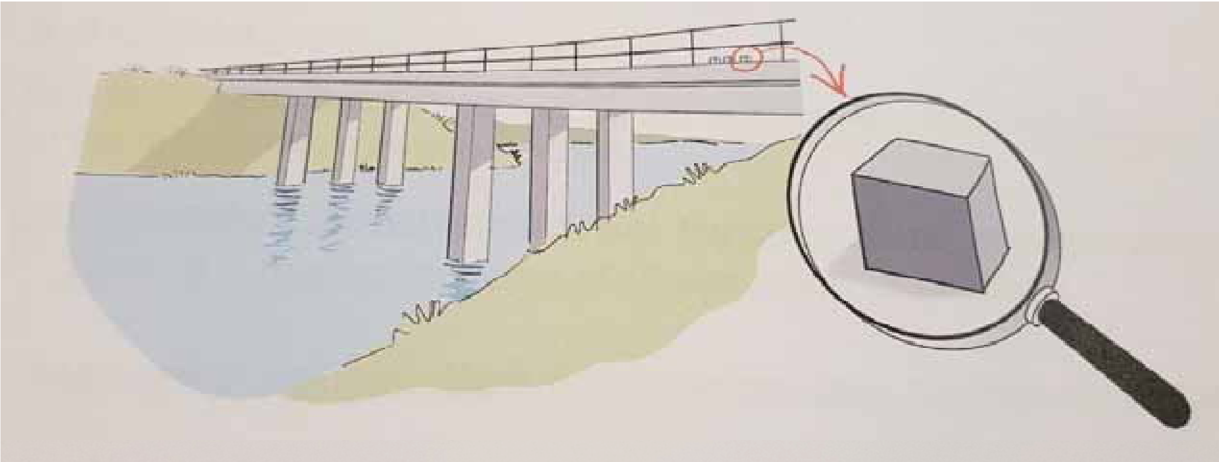
Kontrola saglasnosti sa uslovima projekta konstrukcije pomaže u tome da se obezbedi sigurnost da proizvod – beton – ispunjava očekivanja odnosno propisane kriterijume [1]. Prema zvaničnim zakonskim propisima Republike Srbije u oblasti betona, za dokaz čvrstoće betona mogu da se koriste uzorci kao što su kocke, prizme i cilindri različitih dimenzija. Za konačni dokaz, svi rezultati preračunavaju se na kocke ivice 20 cm. Uvođenjem evropskih propisa, u Republici Srbiji – na gradilištima i u laboratorijama – osnovni uzorci će biti kocke ivice 15 cm. U skladu s važećim standardima, za ocenu betona u konstrukciji propisana je odgovarajuća nega koja je u potpunosti drugačija od nege elementa u konstrukciji. Za neke faze građenja konstrukcije uzimaju se dodatni uzorci koji se čuvaju u istim uslovima kao odgovarajući elementi u konstrukciji. Oni se koriste kako bi se odredilo optimalno vreme oslobađanja elementa od oplate, utezanja konstrukcije i slično. Ipak, u slučaju masivnih konstrukcija i elemenata konstrukcije sa značajnim dimenzijama, poređenje betona u kocki i konstruktivnom elementu pod znakom je pitanja. O kakvom disparitetu je reč, prikazano je na slici 1, na kojoj se jasno vidi kolika može biti razlika u veličini između kontrolnog uzorka i konstrukcije. U slučaju, na primer, prednapregnutih konstrukcija, broj uzoraka na gradilištu znatno se povećava i neophodna je dobra koordinacija kontrolne laboratorije sa izvođačem radova, kako bi se na vreme dobio podatak o čvrstoći betona.

Zakonska regulativa Republike Srbije, u oblasti armiranog betona, oslanja se u svemu na još uvek važeći pravilnik BAB'87 [2]. Kada je u pitanju temperatura u betonu, važeći pravilnik BAB'87 definiše maksimalnu temperaturu u masivnim betonskim elementima na nivou od 60°C. Evropske norme su nešto blaže, pa maksimalnu temperaturu u betonu ograničavaju na 70°C [3]. Američki propis za beton ACI 318 [4] ograničava maksimalnu temeperaturu u betonu na svega 55°C. Izgradnja masivnih delova konstrucija posebno je kritična u zemljama hladnih klimatskih prilika. Tako, propisima u Švedskoj, definisana je maksimalna dozvoljena temperatura u betonu svega 55°C, a ograničen je i maksimalni temperaturni gradijent u elementu konstrukcije na 24°C [4–7]. Pored ograničenja temperature i temperaturnog gradijenta, u Švedskoj su propisana tri nivoa proračuna uticaja temperature na konstrukciju pre početka izgradnje, u zavisnosti od vrste i veličine konstrukcije koja se gradi [7].

According to US regulations the control of in-place concrete strength depends on the types and size of structures. There are special methods which are applicable to plate-like elements, whose thickness goes up to 300mm thick, as well as several different ones for all other types and sizes of structures. The most often applied methods are the pull-through resistance test method, the pull-out method and methods based on maturity of concrete. For each of these approaches, there are standard prescribing methods for testing and calculating in-place concrete strength.

The control of compliance with the structure design requirements help to ensure that the product – concrete meets the requirements, i.e., prescribed criteria. [1] According to the legislation of the Republic of Serbia relevant to concrete, samples in the form of cubes, prisms and cylinders of various dimensions are used for the purpose of proving required concrete strength. The final proof is presented as the strength of concrete obtained in 20cm cubes. With the introduction of European regulations, the construction sites across the Republic of Serbia will take a 15cm cube as the basic test cube. For the purpose of evaluation of in-place concrete strength, appropriate curing has been prescribed, according to the applicable standards. The curing prescribed by applicable standards is entirely different from the curing of elements in-situ. For some phases in construction stage additional samples should be taken and kept under the same conditions as the corresponding in-place elements. Such samples are used to determine the optimum time for stripping formwork, for tightening the structure, etc. However, in the case of massive structures and structural elements of significant dimensions, comparing concrete cured in test cubes to in-place concrete is questionable. The kind of required disparity is shown in Figure 1 which clearly shows how much the difference can be in size between the control sample and the construction. For instance, if prestressed structures are used at a construction site, the number of samples is significantly increased and it is necessary to have a good coordination between the activities of the test lab and the contractor of the works for obtaining reliable and timely data on concrete strength.

Serbian Republic regulations related to reinforced concrete rely on the still applicable Rulebook BAB'87 [2]. Regarding temperature in the concrete, the Rulebook BAB'87 allows the maximum temperature in massive concrete elements of 60°C. European norms are a bit more relaxed, limiting the maximum temperature in concrete to 70°C [3]. American concrete institute standard, ACI 318 [4] limits the maximum concrete temperature to only 55°C. The execution of massive parts of structures is critical in the cold climate countries. Thus, Swedish regulations set the maximum concrete temperature at only 55°C, at the same time also limiting the maximum temperature gradient in a structural elements to 24°C [4,7]. Beside maximum temperature and temperature gradient, the Swedish regulations before construction stage also prescribe three levels of calculations of the impact of temperature on the structure, depending on the type and size of the structure. [7].



Slika 1. Uzorci za kontrolu čvrstoće betona, negovani u uslovima kao elementi konstrukcije
Figure 1. Samples for concrete strength testing cured under the same conditions as in-place members

Ocena saglasnosti s propisanim uslovima kvaliteta betona na mestu ugrađivanja – putem uzoraka kocki i bez uzimanja u obzir uticaja temperature – jeste diskutabilna. Rađena su brojna istraživanja i razvijene su metode koje povezuju čvrstoću pri pritisku i temperaturu betona u starostima do 28 dana [8,9]. U istraživanjima su prikazani različiti rezultati i pouzdanost usvojenih metoda, jer su ulazni parametri različiti, a samim tim i zaključci se razlikuju. U prikazanim istraživanjima, različito je i dobijanje ulaznih parametara, kao i njihovo usvajanje, što je najznačajniji uzrok razlika u analizama i zaključcima.

Cilj rada jeste da se na primeru iz prakse građenja masivnih konstrukcija uporedi više predloženih pristupa kontrole i procene čvrstoće betona. Prvo, potrebno je uraditi laboratorijske probe pri konstantnim temperaturama nege, a nakon toga sprovesti merenja temperature u masivnim delovima konstrukcije mosta, uraditi proračun čvrstoće betona i nakon toga uporediti dobijene rezultate. Pored teorijskih pristupa za procenu čvrstoće, koristiće se uređaj *ConReg* 706, pomoću kog može da se procenjuje čvrstoća betona.

The evaluation of conformity with prescribed concrete quality requirements for in-place concrete via test cubes is questionable without taking into account the impact of temperature. Numerous researches have been done and methods have been developed to connect compressive strength and temperature in concrete aged up to 28 days [8,9]. The research shows the different results and reliability of the adopted methods, since the input parameters are different, and thus, the conclusions differ. In the presented research, the acquisition and adoption of input parameters is different, which is the most significant cause of differences in analyzes and conclusions.

The aim of this paper is to compare the proposed approaches to the control and assessment of the concrete strength in the case study of the construction of mass concrete constructions. First, it is necessary to do laboratory tests at constant temperature of curing, and then perform temperature measurements in massive parts of the bridge construction, perform a calculation of concrete strength and then, compare the results obtained. In addition to theoretical approaches for strength assessment, the ConReg 706 will be used to assess the strength of the concrete.

2 TEORIJSKE POSTAVKE

Kvalitet ugrađenog betona, po pravilu, u praksi se kontroliše na uzorcima koji se uzorkuju prilikom betoniranja konstrukcije. Uzorci se neguju u svemu prema standardu. Kada su u pitanju uzorci betona za kritične faze tokom građenja, oni se uglavnom čuvaju u uslovima istim kao i elementi u konstrukciji. Nakon dostizanja zahtevane starosti, uzorci se transportuju u laboratorije radi ispitivanja; nakon dobijanja rezultata, donosi se odluka o izvođenju planiranih faza tokom gradnje. Uzorci – koji se čuvaju u uslovima kao i elementi u konstrukciji – koriste se kako bi se dokazala čvrstoća betona, neophodna za skidanje oplate, faze utezanja i/ili skidanje potpornih elemenata u slučaju ploča i sličnih elemenata.

Osnovno pitanje koje se postavlja jeste da li takvi uzorci (kocke ili cilindri koji se neguju na gradilištu) na

2 THEORETICAL POSTULATES

As a rule, the quality of in-place concrete in practice is controlled using samples taken during the building works. For the first 24 hours, the samples are cured under conditions applicable to in-place elements, i.e., under conditions as similar as possible to those prescribed by the applicable standard. Thereafter, the samples are cured fully in accordance with prescribed standards. Samples of concrete taken in critical phases of building works are kept, as a rule, under the same conditions as in-place elements. When reaching the required age, such samples are transported to laboratories for further testing and, based on the obtained results, decisions are made on proceeding with planned stages in building works. The samples cured under the same conditions as in-built elements are used to prove the strength of the concrete required for strippravi način reprezentuju stanje u betonskoj konstrukciji. Ukoliko se razmatra betoniranje u uslovima niskih temperatura, uzorci koji se neguju na gradilištu imaju znatno niže temperature. U takvim uslovima, uzorci mogu imati drastično manje čvrstoće betona od betona u masivnim delovima konstrukcije. Ako se, pak, razmatra beton u predelima s visokim temperaturama, može doći do znatno viših temperatura u betonskim telima za kontrolu, nego u samoj konstrukciji. U tim slučajevima, mogu se očekivati uočljivo veće čvrstoće betona na uzorcima za kontrolu kvaliteta od betona u konstrukciji. Opisane situacije ukazuju na to da je neophodno kontrolisati temperaturu betona, kako bi se stvorila jasna slika o dostignutim čvrstoćama betona i uporedilo stanje u uzorcima s konstrukcijom.

Istraživači i brojni proizvođači opreme razvili su niz metoda za kontrolu postignute čvrstoće betona u konstrukciji, u zavisnosti od temperature koja se javlja u elementu. Sve razvijene metode zasnivaju se na principu zrelosti betona. Smatra se da hidratacija cementa prestaje na temperaturama oko -10°C, a zrelost betona zavisi od starosti i temperature kojoj je beton bio izložen. Osnova za primenu zrelosti betona u određivanju čvrstoće betona jesu laboratorijska ispitivanja pomoću kojih se određuje zavisnost čvrstoće i zrelosti, nakon čega se dobijena funkcija može primenjivati prilikom izgradnje na terenu, odnosno gradilištu. Funkcije zrelosti betona jesu matematički izrazi za računanje kombinovanog efekta vremena i temperature na razvoj čvrstoće betonskih mešavina odnosno cementnih kompozita. Dva u svetu najviše prihvaćena pristupa jesu: da je nivo razvoja čvrstoće linearno zavisan od temperature odnosno da se razvoj čvrstoće odvija po eksponencijalnoj Arrhenius jednačini. Oba pristupa imaju svoje prednosti, kao i nedostatke. Prvi pristup je veoma jednostavan za korišćenje, ali je manje pouzdan, dok je drugi pristup nešto složeniji, jer zahteva određene dodatne parametre na osnovu većeg broja laboratorijskih ispitivanja, ali je precizniji od prvog pristupa.

Prvi pristup određivanja faktora temperatura–vreme zasnovan je na funkciji zrelosti (1), koju su pedesetih godina prošlog veka predložili Nurse & Saul [8], usvajajući to da je T_0 u rasponu od -8 do -10°C, kao temperatura na kojoj prestaje hidratacija cementa.

ping the formwork, for re-tightening and/or removing supporting structures in the case of slabs and similar members.

The basic question is: whether a cube or a cylinder sampled at the construction site properly reflects the state within the concrete structure. This issue is of particular importance from the aspect of in-place concrete strength, and achieving designed in-place concrete strength. If laying concrete is considered under low environment temperatures, the samples taken in situ would be also considerably cooler. In such cases, the strength of the sampled concrete can be significantly lower than that of the concrete built in massive parts of building structures. On the other hand, in areas characterized by high daily temperatures, concrete in test cubes can be exposed to much higher temperatures than in-place concrete. Hence, test cube concrete can reach much higher strengths than in-built concrete. This proves that in order to obtain a clear and realistic picture of achieved in-place concrete strength and to be able to compare in-place and test concrete samples it is necessary to control the temperature in concrete.

Researchers and manufactures of concrete-related equipment have developed a number of methods for testing in-place concrete strength, depending on temperatures inside the element. All these methods are based on the principle of concrete maturity. The idea of concrete maturity is quite old and based on simple principles. The basic principle is that cement hydration stops at around -10°C, and that maturity of concrete depends on the age, as well as on the temperature that concrete has been exposed to. Laboratory tests, which make correlation between concrete strength and maturity, serve as the basis for using concrete maturity to define concrete strength and later applied in situ, i.e., at the construction site. The functions of concrete maturity are mathematical expressions used for calculating the time-temperature effects on the strength development of concrete mixtures, i.e., cement composites. In general, there are two widely-used approaches; one assumes that the rate of the strength development is a linear function of temperature, and the other assumes that the rate of the strength development follows the exponential Arrhenius equation. Both approaches have advantages and weaknesses. The first is very simple to use but is less reliable while the second is more complex requiring certain additional parameters based on more extensive lab tests but its accuracy is much higher compared to the first approach.

The first approach for defining the time-temperature factor is based on the maturity function (1) proposed in 1950's, by Nurse & Saul [8], which is adopting $T_{0,}$ in the range between -8 and -10°C, as temperature below which hydration stops.

$$M(t) = \sum (T_a - T_0) * \Delta t \tag{1}$$

gde su: $M(t)$ – faktor temperatura – vreme koji se izražava u stepen–dan ili stepen–sat, T_a – srednja temperatura u usvojenim vremenskim intervalima, T_0 – početna temperatura odnosno temperatura nulte hidratacije u betonu, Δt – usvojeni vremenski interval merenja temperature.

Drugi pristup, dosta kasnije predstavljen, zasnovan je na određivanju ekvivalentne starosti pomoću Arrhenius-ove [8] funkcije (2).

where: $M(t)$ = temperature-time factor expressed as degree-days or degree-hours, T_a = average temperature in adopted time intervals, T_0 = starting temperature, i.e., temperature for staring concrete hydration, Δt – adopted time interval for temperature measurement.

The second approach, presented much later, is based on determination of equivalent age using Arrhenius [8] function (2).

$$t_e = \sum e^{-Q\left(\frac{1}{T_a}-\frac{1}{T_s}\right)}\Delta t \quad (2)$$

gde su: t_e – ekvivalentna starost pri specificiranoj temperaturi T_s izražena u danima ili satima, Q – aktivaciona energija, podeljena s gasnom konstantom, u granicama je od 4800 do 5000°K, u zavisnosti od vrste primenjenog cementa u betonu, T_a – srednja temperatura betona u intervalu Δt (°K), T_s – usvojena ili specificirana temperatura izražena u °K i usvaja se na nivou od 20±2°C, Δt – interval merenja, a izražava se u danima ili satima.

Oba pristupa zahtevaju prethodna ispitivanja u laboratorijskim uslovima i na recepturama za beton koje će biti korišćene prilikom betoniranja elemenata konstrukcije.

3 EKSPERIMENTALNI RAD

Kao što je već prethodno rečeno, kontrola postignute čvrstoće betona u konstrukciji jeste obavezna za pojedine faze izgradnje. Naročito je značajno kontrolisati postignutu čvrstoću betona u masivnim elementima, odnosno elementima čija je najmanja dimenzija veća od 1 m. Kada su u pitanju ovakvi elementi, posebno su značajni vremenski uslovi u kojima se radovi izvode, odnosno da li su visoke ili niske ambijentalne temperature. Prilikom izgradnje mostova, svi delovi konstrukcije – osim ploča i glavnih nosača – svrstavaju se u masivne konstrukcije, odnosno primenjuju se pravila za masivni beton.

Prilikom izgradnje mosta preko reke Save kod Ostružnice, za naglavne grede, stubove i ležišne grede najmanja dimenzija elemenata bila je veća od 1 m. Samim tim, ovi elementi morali su se razmatrati kao masivni betonski elementi. Zbog ubrzanja dinamike izvođenja radova i boljeg iskorišćenja oplata, neophodno je bilo da se ovi elementi što pre oslobađaju od oplate.

Urađene su analize receptura za beton klase C30/37 (MB35 i MB40), kao i laboratorijska ispitivanja za dobijanje odnosa čvrstoće pri pritisku i faktora vreme–temperatura ili ekvivalentne starosti.

Za izradu betona, korišćeni su: cement CEM II A/L 42,5R, agregat iz reke Morave, separisan u četiri frakcije s maksimalnim zrnom agregata 32 mm, voda iz vodovoda i superplastifikator na bazi polikarboksilata. Količina cementa bila je 370 kg/m^3 i 400 kg/m^3 za beton MB35 i MB40 respektivno. Količina superplastifikatora bila je konstantna 0.6% u odnosu na masu cementa. Voda je usvojena tako da se dobije beton konzistencije 19 cm ± 2 cm. Spravljanje betona u laboratoriji rađeno je u mešalici kapaciteta 60 l, dok je na gradilištu bila angažovana fabrika betona s kapacitetom mešanja 2 m^3 u mešalici.

Laboratorijska ispitivanja obuvatila su izradu receptura pri spoljašnjoj temperaturi od 20°C i određivanje čvrstoće pri pritisku u starostima od 12h, 18h, 24h (jedan dan), tri dana, sedam dana, 14 dana i 28 dana. Komponentalni materijali za beton čuvani su u laboratorijskim uslovima na temperaturi od 20°C, pa je spravljeni beton, pri mešanju, imao temperaturu od 22°C ± 2°C. Nakon 24 sata nege na vazduhu pri temperaturi od 20°C, dalja nega sprovođena je u vodi konstantne temperature 20 ± 1°C. Temperatura u uzorcima je kontrolisana; već nakon 12 sati od izrade, bila je do

where: t_e = equivalent age at specified temperature, T_s = the same expressed in days or hours, Q = activation energy divided by the gas constant, (°K), T_a = average concrete temperature in time interval Δt, (°K), T_s = adopted and specified temperature, (°K), Δt = time interval of measurement, days or hours.

Both of the above approaches require prior testing in laboratory on the concrete mixtures that will be used during the casting.

3 EXPERIMENTAL WORK

As already mentioned, the control of achieved in-place concrete strength is mandatory in some building stages. It is very important to test concrete strength in massive elements, i.e., in elements whose minimum dimension is 1m or more. Weather conditions at the time of building works have particular importance for such elements, i.e., whether ambient temperatures are high or low. In the bridge construction industry, apart deck slab and main girders, all other elements are considered to be massive parts, i.e., massive concrete elements.

During the construction of the bridge over the river Sava near Ostružnica, the smallest dimensions of built elements, pile cup, piers, and bearing beams, were more than 1m. Therefore, these parts had to be viewed as massive concrete elements. However, for the purpose of acceleration of the works, and better utilization of formwork, it was necessary to strip formwork as soon as possible.

The mix design analyses were carried out and used to prepare concrete class C30/37 (Serbian: MB40 and MB 35), as well as laboratory tests in order to establish the relation between compressive strength and time-temperature or equivalent age factors.

For the production of concrete we used: CEM II A/L 42,5R cement, aggregate from river Velika Morava separated into four fractions with a maximum aggregate grain 32mm, water from water supply and a polycarboxylate based superplasticizer. The amount of cement was 370 kg/m^3 and 400 kg/m^3 for concrete MB35 and MB40 respectively. The amount of superplasticizer was constant at 0.6% relative to the weight of the cement. The water was adopted so as to obtain a concrete consistency of 19cm ± 2cm. Concrete preparation in the laboratory was done in a 60 l mixer, while a concrete plant with a mixing capacity of 2 m^3 in the mixer was engaged on the construction site.

Laboratory tests included production of concrete using the recipes at 20°C and determining compressive strength for concretes aged 12h, 18h, 24h (1 day), 3 days, 7 days, 14 days and 28 days. The constitutive materials for concrete were stored under laboratory conditions at a temperature of 20°C, and the produced concrete was at a temperature of 22°C+2°C at most. After 24 hours of air cure at a temperature of 20°C, the further curing was carried out in a water with constant temperature of 20°C±1°C. The temperature in the samples was controlled and after 12 hours of production it was up to a maximum of 22°C. A constant temperature of 20°C in the case of laboratory tests is taken for the calculation. Three 150mm-test cubes were examined for najviše 22°C. Za proračun je uzeta konstantna temperatura od 20°C u slučaju laboratorijskih proba. U svakoj od predviđenih starosti betona, ispitane su tri kocke ivice 150 mm. Kao rezultat ispitivanja, uzeta je srednja vrednost od tri uzorka, s tim što je rasipanje rezultata ograničeno na 15% od srednje vrednosti. Na osnovu dobijenih rezultata, dobijene su funkcije čvrstoće pri pritisku i faktora vreme–temperatura. Takođe, na osnovu istih rezultata dobijena je i funkcija čvrstoće pri pritisku i ekvivalentne starosti betona. Laboratorijski dobijene funkcije prikazane su na slici 2 za odnos čvrstoće i faktora vreme–temperatura i na slici 3 odnos čvrstoće i starosti betona, a eksperimentalne vrednosti date su u tabeli 1. Za izračunavanje faktora vreme–temperatura, kao referentna temperatura korišćeno je -3°C prema uputstvima brojnih autora [8].

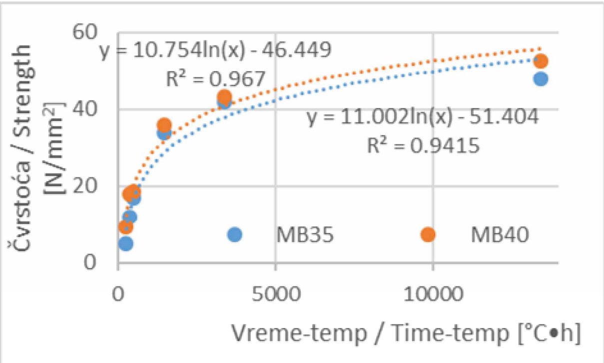
Kompletan eksperimentalni rad urađen je na dve recepture betona – MB35 i MB40. Recepture za beton date su u tabeli 1, kao i postignute čvrstoće betona u predviđenim starostima.

each of the above listed concrete ages. The average value of the results obtained from all three cubes was used as the final result, with scattering of results limited to 15%. The functions of compressive strength and time-temperature factors were calculated based on these obtained results. Also, these results were used to generate the function of concrete compressive strength and equivalent age. The functions obtained by lab testing are shown in Figure 2 for the strength and time-temperature factor relation and in Figure 3 for the concrete strength and age relation, and experimental values are shown in Table 1. Reference temperature of -3°C was used for calculating the time-temperature factor following recommendations of numerous authors [8].

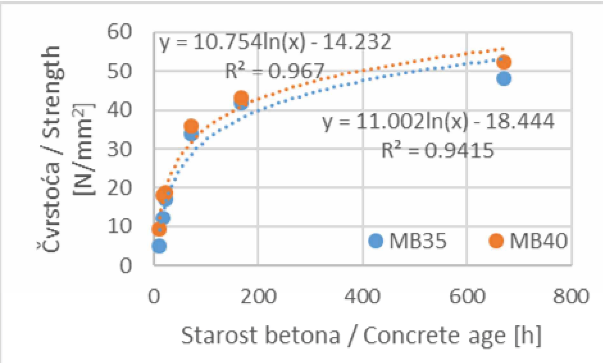
The entire experimental work was done for two concrete recipes, MB35 and MB40. The concrete recipes are given in table 1 as well as achieved concrete strengths at specified age.

Tabela 1. Rezultati laboratorijskih ispitivanja za MB35 i MB40
Table 1. Results of laboratory tests for MB35 and MB40

Marka betona *Concrete*	Cement *Cement* kg/m^3	Voda *Water* kg/m^3	Agregat *Aggregate* kg/m^3	Plastifik. *Plast.* kg/m^3	Aerant *"Aerant" additive* kg/m^3	12h MPa	18h MPa	24h MPa	3d MPa	7d MPa	28d MPa
MB35	371	162	1795	2.6	0.03	5.1	12.1	17.1	34.1	42.0	48.1
MB40	400	170	1742	2.8	0.032	9.3	18.1	18.7	35.9	43.2	52.5



Slika 2. Odnos čvrstoće i vreme–temperatura
Figure 2 Strength and time-temperature relation



Slika 3. Odnos čvrstoće i starosti betona
Figure 3 Strength and concrete age relation

Kada je završena faza laboratorijskih ispitivanja betona za dve marke betona, pristupilo se merenjima na gradilištu. Merenje je sprovedeno pomoću aparata *ConReg* 706 firme ASTM iz Švedske. Uređaj ima mogućnost da meri temperature na maksimalno šest mesta u konstrukciji i – na osnovu sopstvene funkcije za određivanje zrelosti betona i čvrstoća određenih u laboratorijskim uslovima – daje procenu čvrstoće u svakom momentu. Funkcija zrelosti betona zasnovana je na principu određivanja ekvivalentne starosti koju su razvili proizvođači opreme, a koja predstavlja modifikovanu Arrhenius funkciju (3).

In situ measurements started once the laboratory testing for both above mentioned concrete mixtures was finished. Measurements were taken using a device ConReg 706 provided by ASTM, a Swedish company. The device has a possibility to take temperature measurements at up to 6 points on the structure and to produce its own evaluation of concrete strength at all times based on its ability to determine concrete maturity and taking into account strengths determined under lab conditions. The concrete maturity function is based on the principle of establishing equivalent age developed by the equipment manufacturer and it represents a modified Arrhenius function (3).

$$t_e = e^{\left\{\left(\left(\frac{\theta}{T+10}\right)^{k_3}\right)*\left(\frac{1}{293}-\frac{1}{T+273}\right)\right\}} \quad (3)$$

gde se koeficijenti k_3 i θ izračunavaju iz laboratorijskih ispitivanja cementa i betona.

Merenja su urađena na više vrsta elemenata - na kolovoznoj ploči, stubu, naglavnoj gredi i ležišnoj gredi. Od izabranih elemenata, samo kolovozna ploča ne pripada masivnim delovima konstrukcije, jer je njena najmanja dimenzija svega 22 cm, što je daleko manje od uslova da najmanja dimenzija elementa bude veća od 1 m.

Kao proba, prvo su urađena merenja temperature betona na kolovoznoj ploči za koju je korišćen beton MB40. Rezultati ispitivanja na kockama čuvanim u uslovima elementa i prognozirane čvrstoće pomoću aparata *ConReg* 706 firme ASTM dati su u tabeli 2 za prva 24 sata starosti betona.

where coefficients k_3 and θ are derived based on the results of laboratory tests of cement and concrete.

Measurements were taken on several types of members: deck slab, pile cup and bearing beam. Among all these elements, only the deck slab does not belong to massive parts of a structure since its shortest edge is only 22cm long, that is, far below the 1m requirement for considering a structure to be a massive one.

Temperature measurements were taken on the deck slab first. The results of tests performed on cubes kept under the same conditions as elements and strengths forecasted by ConReg 706 devices provided by ASTM company are shown in table 2 for the fists 24 h of concrete aging process.

Tabela 2. Uporedna ispitivanja na kolovoznoj ploči
Table 2 Comparative tests for deck slab

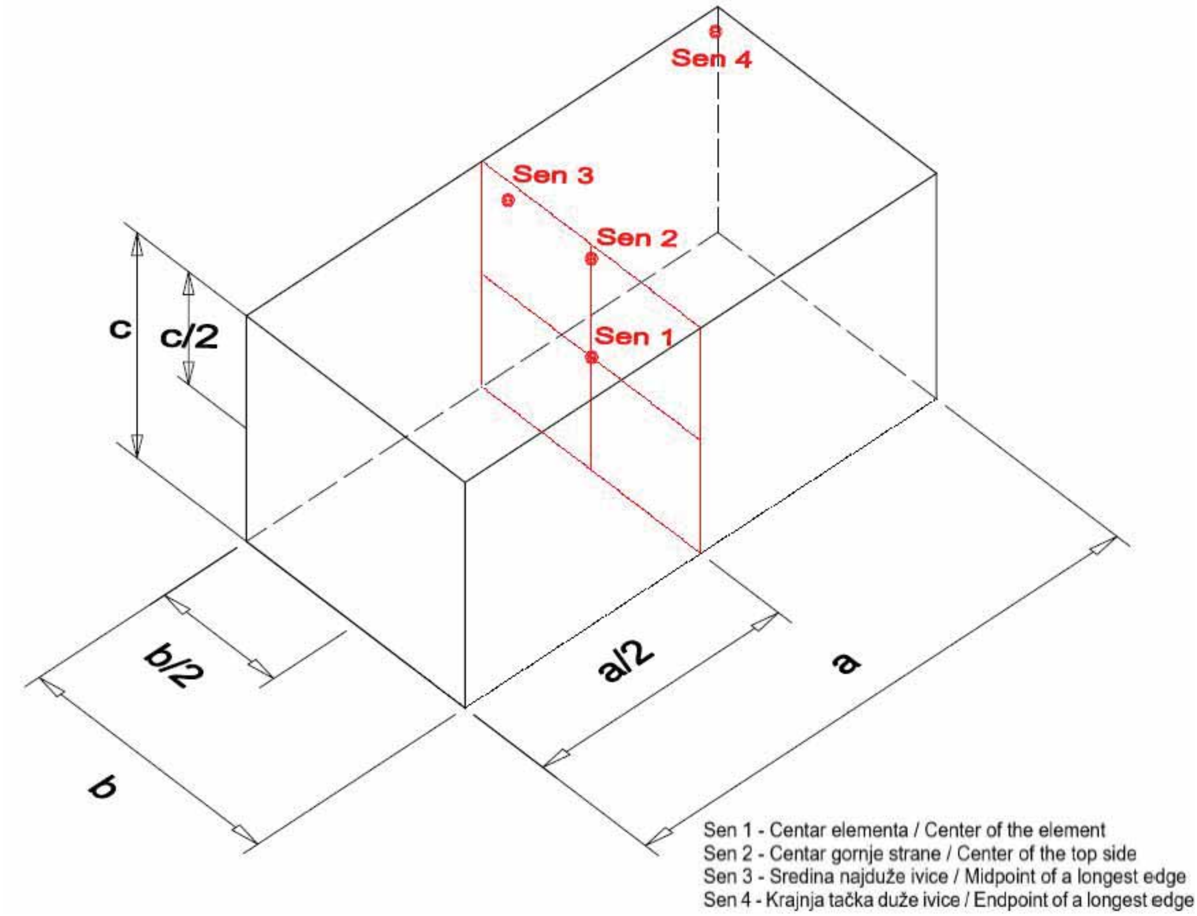
Marka betona Concrete Class	*Vreme Time*	*Čvrstoća na kockama Strength on cube*	*Procena na ConReg Evalution on ConReg*
MB40	*12h*	*13.75 N/mm^2*	*14.61 N/mm^2*
	18h	*24.16 N/mm^2*	*23.13 N/mm^2*
	24h	*30.14 N/mm^2*	*30.05 N/mm^2*

Nakon ispitivanja urađenih na kolovoznoj ploči, pristupilo se pripremi i ispitivanjima na naglavnoj i ležišnoj gredi koje su betonirane betonom MB35. Tokom pripremnih radova, urađena je analiza oba elementa i određena su potencijalna mesta na kojima će biti rađeno merenje i paralelno ispitivani kontrolni uzorci. Naglavna i ležišna greda su izabrane jer je reč o dva potpuno različita elementa iz aspekta temperaturnih uticaja. Naglavna greda je ukopan element, odnosno radi se u širokom iskopu, ali je donja strana kompletno na zemlji, odnosno na mršavom betonu, te s donje strane nema oplate. Bočne strane su na 1–1.5 m od iskopa i ovakav element, osim s gornje strane, zaštićen je od direktnog uticaja sunca. Gornja površina se na svim elementima posle 6 do 8 sati od betoniranja zaštićuje geotekstilom i počinje se s negom betona već posle 12 sati. Drugi izabrani element – ležišna greda – jeste deo konstrukcije iznad stuba i za takav element, osim na relativno malom delu stuba na koji se oslanja, oplata je neophodna sa svih strana. Kod ležišne grede vazduh je sa svih strana. Kod ovakvog elementa konstrukcije spoljašnji uticaji su vrlo važni, naročito leti kada direktni sunčevi zraci mogu povisiti temperaturu oplate, a samim tim i betona.

Prvo je urađeno ispitivanje na naglavnoj gredi dimenzija 9.5x2.4x2.5 m, a potom i na ležišnoj gredi dimenzija 12.6x2x (~2 m) – širina grede promenljiva je od 2 do 1.5 m. Temperatura je merena na četiri mesta u konstruktivnom elementu i u okolini elementa koji je betoniran. Šematski prikaz rasporeda senzora u konstrukciji tokom merenja temperature u oba elementa dat je na slici 4.

After the tests on the deck slab were performed, there have been some preparations and testing on the pile cup and bearing beam. The preparation works included an analysis of both elements and choosing potential spots in the elements suitable for measurements and parallel control of test samples. These components had been selected because they were completely different from the aspect of temperature impact. The first component was the pile cup that is an embedded structure. More precisely, there was a wider excavation and the bottom side of the component was laid completely on the ground, i.e., lean concrete surface which means no formwork was placed there. The sides of the components were located 1-1.5 m far from the excavation and this member, save for its upper side is completely protected from direct impact of the sun. The upper surface of all these elements should be protected from the sun 6 to 8 hours after concreting with geotextile fabric material and the curing process should start 12 hours after casting. The second structural component selected for the test – the bearing beam is a part of the structure above the pillar and as such it requires formwork to be placed from all sides except for a relatively small part where the component rests of the pillar. The bearing beam is exposed to air from all sides. In the case of such element, external impacts are significant, especially in summer when direct sun exposure can increase the temperature of formwork and thus, of the concrete as well.

Measurements were taken first on the pile cup dim. 9.5x2.4x2.5m, and then on the beam dim. 12.6x2x(~2m) (the width of the beam varies between 2 and 1.5m). Temperature was taken at four points in the element as well as the temperature of the external air close to the casting place. Schematic diagram of measurement points in both elements is shown in Figure 4.



Slika 4. Raspored senzora u ispitivanim elementima
Figure 4. Disposition of sensors in tested elements

Pored prikazanih senzora, korišćen je i peti senzor za merenje temperature vazduha u okolini elementa. Taj senzor postavljen je u zaštitnu drvenu kutiju koja je sprečavala direktni uticaj sunca i na taj način omogućeno je pravilno merenje temperature vazduha u okolini elementa.

Sva merenja rađena su tokom sedam dana. Uređaj firme ASTM *ConReg* 706 podešen je da beleži rezultate u intervalu od 30 minuta, pa je dobijena baza od oko 300 merenja po razmatranom elementu. Uređaj beleži temepraturu i daje procenu čvrstoće prilikom svakog merenja.

Na osnovu merenja temperature, urađen je proračun čvrstoće betona pri pritisku na osnovu dva opisana pristupa. Pored ova dva pristupa, uređaj *ConReg* 706 dao je procenu čvrstoće betona. Na osnovu dobijenih rezultata, data su tri para krivih za procenu čvrstoće betona: prva korišćenjem Nurse & Saul funkcije, druga korišćenjem Arrhenius funkcije i treća je dobijena iz uređaja *ConReg* 706. Za sve navedene pristupe, dobijene su po dve funkcije: za mesta s najnižom i najvišom temperaturom u elementu. Svi dobijeni rezultati prikazani su u obliku dijagrama na slikama 5 i 6. Na slikama su prikazane krive dobijene korišćenjem Nurse & Saul pristupa (Str-1 i Str-3), krive na osnovu Arrhenius-ove formule (Str-1 Arrh i Str-3 Arrh) i krive

In addition to the above displayed sensors, a fifth sensor was also used for measuring environmental air temperature. This sensor was encased in a protective wooden box preventing direct exposure to the sun, thus enabling proper measurement of air temperature close to the tested component.

The entire measurement lasted for 7 days. The ASTM supplied device, ConReg 706 was adjusted to record results at 30-minute intervals, thus creating a database containing 300 measurements per tested element. The device is designed to record temperature and produce its own evaluation in terms of strength after each measurement.

Based on temperatures taken on the elements the compressive strength of concrete was calculated using two traditional approaches. In addition to these approaches, the ConReg 706 device also produced its own concrete strength evaluation. On the basis of the obtained results, three pairs of curves for the concrete strength assessment were given: first using the Nurse & Saul function, the second one using the Arrhenius function, and the third was obtained from the ConReg 706. For all the foregoing approaches, two functions have been obtained: for the places with the highest and for the places with the lowest temperature in the member. All of the results thus obtained are shown in dobijene iz uređaja *ConReg* 706 (ConR1 i ConR2). Na slikama su paralelno prikazana i merenja spoljašnje temperature (AirTemp) u okolini predmetnog elementa.

4 ANALIZA REZULTATA I ZAKLJUČCI

Prikazani rezultati ispitivanja navode na više zaključaka u razmatranju uticaja temperature na razvoj čvrstoće betona.

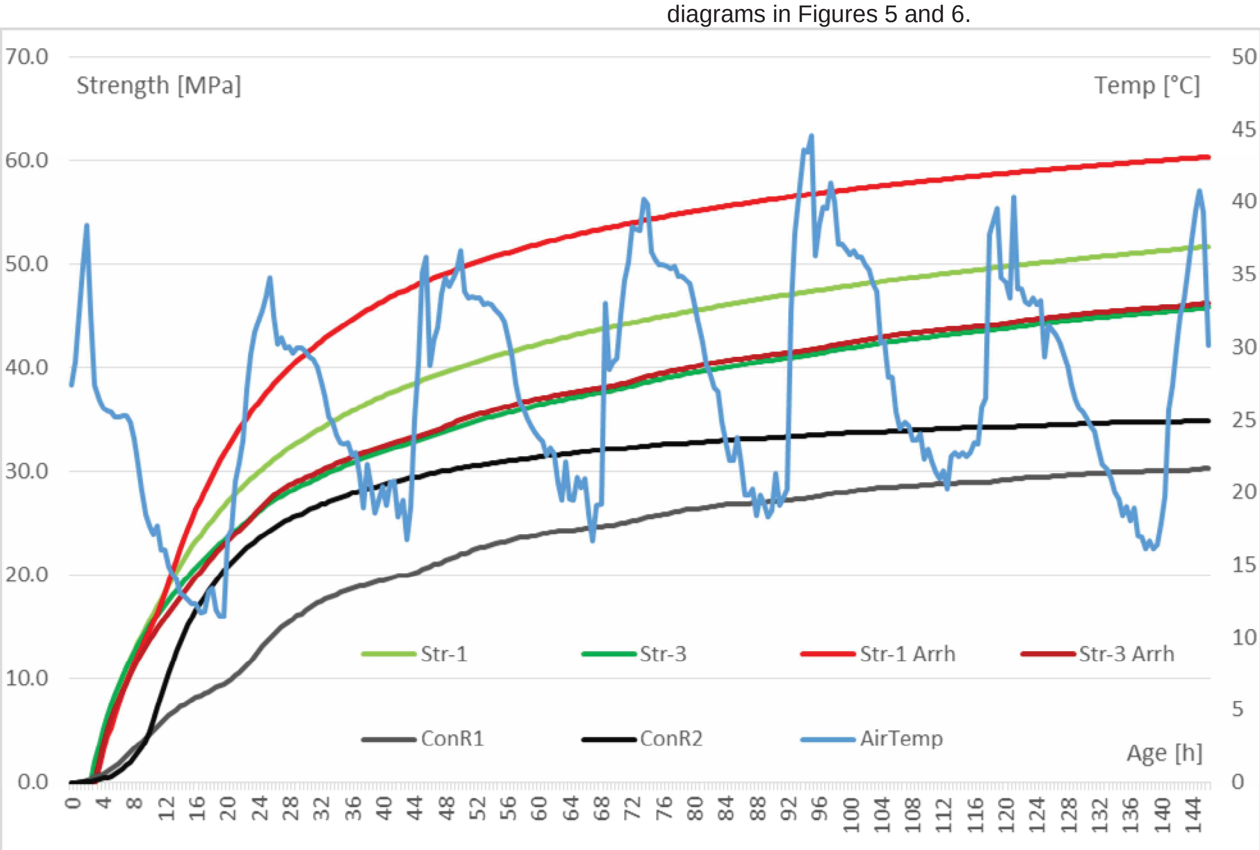
Izabrane metode ispitivanja veoma su osetljive na izbor mesta merenja temperature betona. Iz prikazanih rezultata vidi se da u okviru svakog pristupa postoje znatna odstupanja, u zavisnosti od mesta merenja. Na dijagramima sa slike 5 i slike 6, vide se razlike za svaki od korišćenih pristupa. Ako se pojedinačno posmatraju primenjene analitičke metode za procenu čvrstoće, za mesta s najnižom temperaturom dobijaju se i preko 15% manji rezultati čvrstoće pri pritisku nego za mesta s najvišom izmerenom temperaturom u elementu. Čvrstoća betona, ako se procenjuje na bazi Arrhenius-ove formule, osetljivija je na promene temperature. Za iste rezultate merenja temperature ovaj pristup daje mnogo veći raspon rezultata nego Nurse & Saul pristup, što se jasno vidi sa dijagrama na slikama 5 i 6.

the form of diagrams in Figures 5 and 6. Figures show the curves obtained using the Nurse & Saul approach (Str-1 and Str-3), curves based on the Arrhenius formula (Str-1 Arrh and Str-3 Arrh) and the curves obtained from ConReg 706 (ConR1 and ConR2). The figures also show the external temperature measurements (AirTemp) in the surroundings of the subject element.

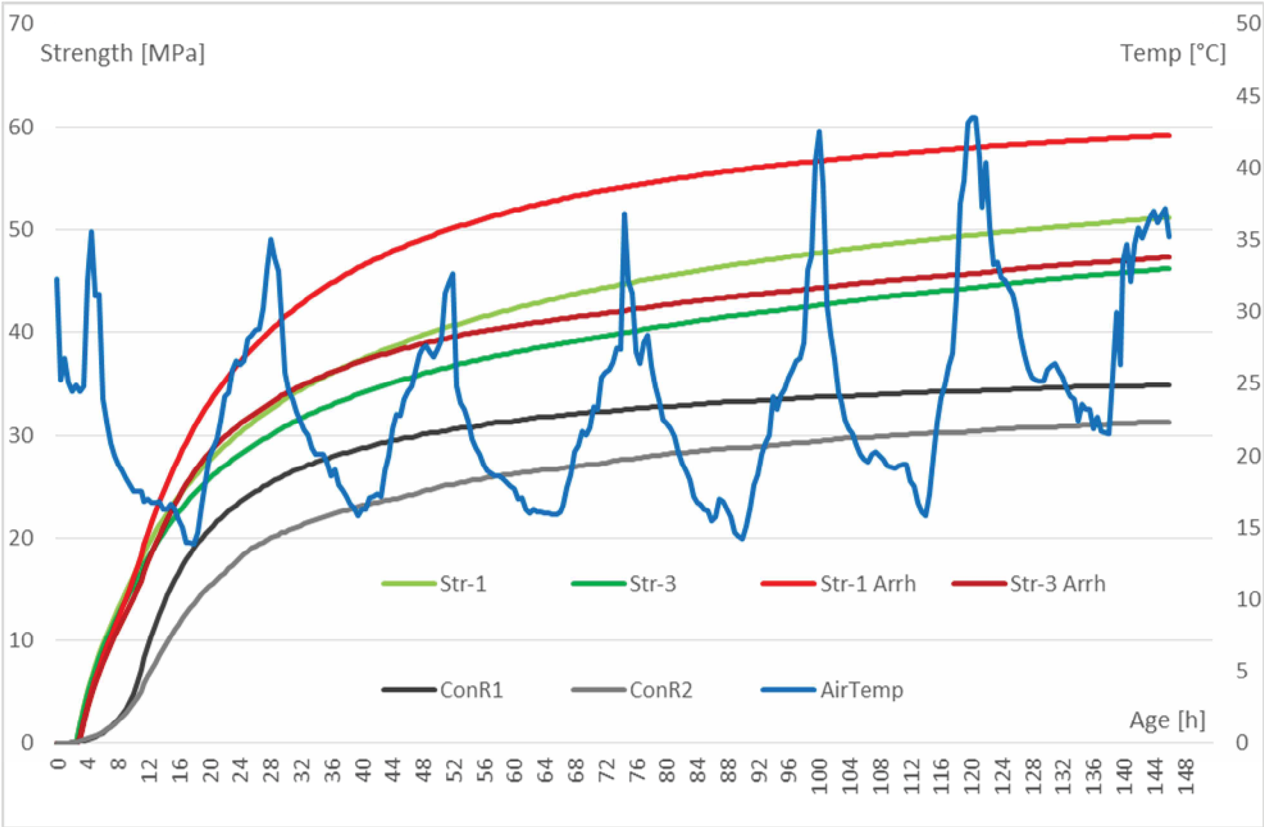
4 THE ANALYSIS OF THE RESULTS AND CONCLUSIONS

Based on the found results, several conclusions can be drawn when considering the influence of temperature on concrete strength.

The selected test methods are very sensitive to the choice of spots for measuring concrete temperatures. The above results clearly show that each approach has significant deviations depending on the measurement place. Figures 5 and 6 clearly show the differences for each of the applied approaches. If the applied analytical methods for assessing the strength for places with the lowest temperature are observed individually, more than 15% less results of compressive strength are obtained in relation to the sites with the highest emission temperature in the element. The strength of the concrete, if assessed on the basis of the Arrhenius formula, is more sensitive to temperature changes. For the same temperature measurement results, this approach gives a much greater range of the results than the Nurse & Saul approach, which is clearly seen in the diagrams in Figures 5 and 6.



Slika 5. Merenja temperature i procena čvrstoće betona u naglavnoj gredi
Figure 5. Temperature measurements and evaluation of concrete strength in pile cup



Slika 6. Merenja temperature i procena čvrstoće betona u ležišnoj gredi
Figure 6. Temperature measurements and evaluation of concrete strength in the bearing beam

Analizirajući rezultate dobijene primenom tri pristupa, uočavaju se znatne razlike u proceni čvrstoće pri pritisku. Generalno uzevši, od svih proračunskih modela, najmanje rezultate daje Nurse & Saul pristup, dok su najveći rezultati dobijeni pristupom koji je koristio Arrhenius-ovu formulu. Proračunske metode veoma su osetljive na temperaturne razlike koje se svakako javljaju u masivnim betonskim elementima. Razlike između klasičnih metoda i proračunskog modela koji koristi uređaj *ConReg* 706 jesu značajne, što svakako treba imati u vidu prilikom odabira metode koja će se koristiti.

Uređaji, kao što je i korišćeni *ConReg* 706 Švedske firme ASTM, paralelno mere temparaturu i daju procenu čvrstoće betona, pa samim tim mogu umnogome olakšati procenu postignute čvrstoće betona u konstrukciji.

Najveće dobijene temperature u elementima dostigle su 70°C, što je daleko više od 60°C, koliko je propisano u Pravilniku BAB'87. Ipak, nije premašena temperatura propisana evropskim normama, te stoga nisu primenjivane mere za smanjenje temperature betona u posmatranim elementima. Ukoliko se kao referentne norme usvoje Švedske norme, premašena je maksimalna temperatura u elementima od 55°C, kao i temperaturni gradijent u elementu od 24°C. Sve to ukazuje na potrebu da se važeća regulativa Republike Srbije mora revidirati u pogledu temperaturnih uticaja u betonskim elementima i približiti savremenim pogledima i istraživanjima u ovoj oblasti.

Analyzing the results obtained using the three approaches, significant differences in pressure strength assessment are observed. Generally speaking, from calculating models, the least results are provided by the Nurse & Saul approach, while the highest results are derived from the approach used by the Arrhenius formula. The classic calculating methods are very sensitive to temperature differences that certainly occur in massive concrete elements. Differences between conventional methods and calculation model which uses a device ConReg 706 are significant which should certainly be kept in mind when selecting the method.

Instruments, as well as the used ASTM ConReg 706 from Sweden, are simultaneously measuring the temperature and providing an estimate of the strength of the concrete, and therefore can significantly facilitate the estimate of the strength of the concrete in the construction.

The highest measured temperature in the elements reached 70°C, which is far more then 60°C maximum allowed in Serbian regulations, Rule book BAB'87. However, maximum temperature defined by European standards was not exceeded, thus no measures were taken to reduce the concrete temperature in tested elements. If the standard adoption of the Swedish standard, the maximum temperature in the elements of 55°C is exceeded as well as the temperature gradient in the element of 24°C is exceeded. All this points to the need for the valid regulations of the Republic of Serbia to be revised in terms of temperature influences in concrete elements and bring them closer to contemporary views and research in this area.

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REZIME

PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM RAZLIČITIH FUNKCIJA ZRELOSTI BETONA: PRIMER IZ PRAKSE

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Čvrstoća pri pritisku jeste svojstvo koje je veoma značajno u građevinarstvu, te postoji izražena potreba da se razviju metode za praćenje prirasta čvrstoće pri pritisku betona u konstrukciji. Prema zakonskim propisima Republike Srbije, procena čvrstoće pri pritisku betona u konstrukciji radi se na osnovu rezultata dobijenih tokom laboratorijskih ispitivanja u konstantnim uslovima.

U radu se koriste rezultati dobijeni u laboratoriji i porede se rezultati dobijeni pomoću metode za merenje zrelosti betona, koje se baziraju na korelaciji između čvrstoće betona, starosti betona i temperaturnih uslova i rezultata dobijenih pomoću *ConReg* 706 uređaja, koji takođe uzima u obzir temperaturu van betona. Primenjena su dva pristupa za određivanje zrelosti betona – Nurse & Saul i Arrhenius.

Za potrebe ovog istaživanja, pripremljene su dve različite betonske mešavine – MB 35 i MB 40, obe klase C30/37. Odabrani konstrukcijski elementi betonirani su tokom leta, na mostu preko reke Save, kod Ostružnice, u blizini Beograda. Testirani elementi mosta jesu kolovozna ploča, naglavna greda i ležišna greda.

Ispitivanje je pokazalo da temperatura koja se razvija u masivnim delovima konstrukcije znatno utiče na čvrstoću betona, pored već dobro poznatih faktora, kao što su vodo-cementni odnos, tip i kvalitet komponentnih materijala i drugi.

Ključne reči: zrelost betona, masivni beton, temperatura

SUMMARY

ASSESMENT OF CONCRETE COMPRESSIVE STRENGTH USING DIFFERENT MATURITY FUNCTIONS: CASE STUDY

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Compressive strength is a property of significant importance for civil engineering; consequently, there have been strong need for developing method, which will estimate rise of concrete compressive strength in construction. According to Serbian legislation, assessment of compressive strength in construction relies on laboratory results obtained under constant conditions.

This paper presents and compares results obtained in laboratory, results obtained by maturity method, which is based on correlation between concrete compressive strength, concrete age and ambient temperature, and the results obtained by ConReg 706 instrument, which also takes in consideration external environment and concrete temperature. Two approaches of maturity method, Nurse & Saul and Arrhenius have been applied.

For this research, concrete class C30/37 was used, prepared as two different mix designs, MB35 and MB 40. Casting was performed in summer time in Ostruznica bridge near Belgrade. Elements that were casted are deck slab, pile cup and bearing beam.

Key words: concrete maturity, mass concrete, temperature