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Construction of a new day hospital in Zadar using recycled aggregate concrete

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Professional Paper

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This paper presents the pilot project of application of recycled aggregate during construction of a new day hospital in Zadar. The project included the demolition of an existing hospital building and the use of generated construction waste as recycled aggregate in the construction of a part of the building. The 16/32 mm fraction of aggregate was obtained by mechanical processing of the generated waste which was then tested in accordance with the HRN EN 206 and HRN EN 12620 standards. Four concrete mixes were prepared, and the fresh (slump, density, air content) and hardened properties were tested (compressive strength, modulus of elasticity, capillary absorption, water permeability, drying shrinkage). The obtained results confirm that by complying with the standards for recycled aggregates and knowing their origin it is possible to produce concrete with properties equivalent to those of ordinary concrete for specified durability conditions.

Key words:
construction & demolition waste, demolition, recycled aggregate, recycled aggregate concrete

Stručni rad

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Primjena betona od recikliranog agregata tijekom izgradnje nove zgrade dnevne bolnice u Zadru

U radu je prikazan pilot projekt primjene recikliranog agregata tijekom izgradnje nove zgrade dnevne bolnice OB Zadar. Projekt je uključivao rušenje postojeće bolnice i korištenje nastalog građevnog otpada kao recikliranog agregata u izgradnji dijela nove zgrade. Mehaničkom obradom nastalog otpada dobivena je frakcija 16/32 mm agregata te je on ispitan u skladu s normama HRN EN 206 i HRN EN 12620. Pripremljene su četiri mješavine betona i provedena ispitivanja svojstava u svježem stanju (konzistencija, gustoća, količina pora) i očvrsnulom stanju (tlačna čvrstoća, modul elastičnosti, kapilarno upijanje, vodonepropusnost, skupljanje uslijed sušenja). Ostvareni rezultati potvrđuju da se uzimanjem u obzir normi za reciklirani agregat te poznavanjem porijekla, za dane uvjete trajnosti može pripremiti beton svojstava istovrijednih običnom betonu.

Ključne riječi:
građevni otpad, rušenje, reciklirani agregat, beton s recikliranim agregatom

1. Introduction

Qualitative waste management means reducing mass production of new waste, finding ways to recycle and reuse existing waste and, finally, disposal of unused waste in a safe and environmentally sound manner [1]. According to Waste Framework Directive i.e., pursuant to article 55 of the Act on Sustainable Waste Management [2], the goal was to increase the recycling, reuse, and other methods for recovery of non-hazardous construction waste, to a minimum of 70 % by weight until 2020. According to the data provided by the Ministry of Environmental Protection and Energy, an estimated quantity of 1,243,642 tons of construction waste was generated in the Republic of Croatia in 2018 [3]. What gives ground to concern is the fact that 95 % of construction waste is inert, i.e. not subject to physical, chemical or biological changes, and that only 58 % of this waste is actually recycled. It is however encouraging that a 16 % increase over the previous year has been noted [3].
Construction waste is considered a special category of waste and, according to the Act on Sustainable Waste Management OG 94/13 [2], it is defined as the waste generated from the construction, reconstruction, demolition, and maintenance of existing buildings, as well as the waste from excavation process that cannot be used, without prior recovery, for construction of the building for which it was generated. According to the Waste Catalogue (OG 90/15) [4], construction waste is identified with a key number from category 17, while data on the generated and accepted quantities of construction waste are kept in the Environmental Pollution Register. In order to prevent generation of waste and ensure proper implementation of waste-management regulations and policies, the following waste management order of priority has been adopted:

- waste prevention
- preparation for reuse
- recycling
- other recovery processes e.g., energy recovery
- waste disposal.

In order to improve the recycling rate, the European Union issued an EU Construction & Demolition Waste Management Protocol in 2016 [5]. According to this protocol, pre-demolition audit has to be conducted in order to identify materials that can be reused or recycled, and to identify hazardous waste. This step gives information about types and quantities of waste, and how the waste will be managed. Furthermore, a waste management plan must be prepared in order to describe demolition operations, selective collection of materials, types of materials, methods of storage and transport to landfill, as well as treatment methods. The protocol covers occupational safety issues, as well as environmental impacts including potential leaching and dust. Demolition work should be carried out selectively, with separation of waste, while main waste streams, including inert construction waste, should be treated separately (e.g. concrete, bricks, masonry, tiles, and ceramics). This will allow reuse, but previously, all available disassembly methods should be considered, including techniques such as removal (before demolition) and rinsing (after demolition). This particularly concerns: glass, timber, sanitary ware, central heating boilers, radiators, window frames, lighting fittings, structural steelwork, and cladding. Other materials that may be considered for reuse or recycling are plaster, insulating foams, concrete, mineral wool, and glass wool. Selective demolition and waste separation allow for the reuse and recycling of the materials themselves, but an additional aim is to clean up the main waste stream (i.e. inert waste intended for production of recycled aggregates). It is important to take precautions to ensure that hazardous waste, which may contain asbestos, tar, radioactive waste, PCBs, lead, mercury, etc., is not mixed with other categories of waste.
During separation, collected material is divided into material for reuse, recycling, other recovery, or disposal. Reuse includes any process that allows products, or their components that are not waste, to be reused for the same purpose for which they were originally produced [5]. On the other hand, recovery is any process whose main result is the use of waste for useful purposes by replacing other materials that should otherwise be used for that purpose, or use of waste prepared for that purpose in the factory or in the wider economic sense [5]. There is a difference between material recovery, which is actually recycling, and recovery for energy purposes. By definition, recycling is any recovery operation, including reprocessing of an organic material, by which waste materials are converted into products, materials or substances for the original purpose or for other purposes, but not the use of waste for energy purposes or for processing into a material that is used as fuel or fill material [5].
It is important to emphasise that quality management control is crucial at all stages: at the construction or demolition site, during waste transport, and at recycling facilities. Good-quality documentation and application of appropriate procedures that can ensure traceability, are important in all phases. Therefore, the aim of this paper is to present advantages and limitations of using recycled aggregates, and to propose a specific sequence of actions, from the demolition to the construction site, the aim being to enable easy replication of the implemented procedures, and their wider application in the future.

1.1. Classification of coarse recycled aggregates

Natural aggregate is obtained by processing materials found in nature without changing their composition. There are two types of aggregate: river aggregate and crushed aggregate. Manufactured aggregate is obtained by processing the material and changing its composition, while recycled aggregate is obtained by crushing the material that has already been used in construction [6]. The recovery and reuse of waste as a substitute for natural aggregate reduces quantities of the existing and new waste, while also protecting the environment through reduced need for the exploitation of natural resources [1]. In the Republic of Croatia, recycled aggregates are regulated by HRN EN 206 [7] and HRN EN 12620 [8] standards. Classification of a coarse recycled aggregate is crucial for defining its future application. Depending on its origin, it is divided into six main categories, as shown in Table 1.

Table 1. Classification of recycled aggregates according to HRN EN 12620 [8]

Constituent	Content (wt. %)	Category
R_c - concrete, concrete products, mortar, concrete masonry units	≥ 90	R_{c90}
	≥ 80	R_{c80}
	≥ 70	R_{c70}
	≥ 60	R_{c60}
	≥ 50	R_{c50}
	< 50	$R_{c,declared}$
	No requirement	R_{cuNR}
$R_c + R_u$ - unbound aggregate, natural stone, hydraulically bound aggregate	≥ 95	R_{cu95}
	≥ 90	R_{cu90}
	≥ 70	R_{cu70}
	≥ 50	R_{cu50}
	< 50	$R_{cu,declared}$
	No requirement	R_{cuNR}
R_b - clay masonry units, calcium silicate masonry units, aerated concrete	≤ 10	R_{b10}
	≤ 30	R_{b30}
	≤ 50	R_{b50}
	>50	$R_{b,declared}$
	No requirement	R_{bNR}
R_a - bituminous materials	≤ 1	$R_{a(1-)}$
	≤ 5	$R_{a(5-)}$
	≤ 10	$R_{a(10-)}$
$X + R_g$ - glass and other materials	≤ 0.5	$XR_{g(0.5-)}$
	≤ 1	$XR_{g(1-)}$
	≤ 2	$XR_{g(2-)}$
FL - floating material	≤ 0.2[a]	$FL_{(0.2-)}$
	≤ 2	$FL_{(2-)}$
	≤ 5	$FL_{(5-)}$

Table 2. Maximum proportion of recycled aggregate depending on the type of aggregate and exposure class [8]

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes
Type A	50 %	30 %	30 %	0 %
Type B	50 %	20 %	0 %	0 %

Table 3. Overview of recycled aggregate tests according to HRN EN 12620 [8]

Property	Type	Category
Fines content	A + B	Value to be declared
Flakiness Index	A + B	≤ FI_{50} or SI_{55}
Resistance to fragmentation	A + B	≤ LA_{50} or SZ_{32}
Oven dried particle density	A	≥ 2100 kg/m³
	B	≥ 2100 kg/m³
Water absorption	A + B	Value to be declared
Constituents	A	R_{c90}, R_{cu95}, $R_{b(10-)}$, $R_{a(1-)}$, $FL_{(2-)}$, $XR_{g(1-)}$
	B	R_{c50}, R_{cu70}, $R_{b(30-)}$, $R_{a(5-)}$, $FL_{(2-)}$, $XR_{g(2-)}$
Water soluble sulphate content	A + B	$AS_{0.2}$
Acid-soluble chloride ion content	A + B	Value to be declared
Influence on initial setting time	A + B	≤ A_{40}

Basic guidelines for the use of recycled concrete as coarse aggregate are given in Annex E of HRN EN 206 [7]. An aggregate is classified as recycled if the proportion of recycled aggregate in relation to the total aggregate content is no less than 5 %. Furthermore, the standard differentiates two types of recycled aggregate: type A is used in a maximum proportion of 50 % and its origin is known, while type B should not be used for concrete with the compressive strength class higher than C30/37. The maximum percentage of recycled aggregate in concrete, determined by the type of aggregate and exposure class, is given below in Table 2.
Recommendations for testing coarse recycled aggregates are given in HRN EN 12620 [8] and include testing of basic physical and chemical properties of aggregates to identify potentially hazardous substances that could adversely affect concrete properties in the long term. The properties and criteria for recycled aggregate are listed in Table 3.

1.2. Influence of recycled aggregate on concrete properties

To gain a better insight into the use of concrete with recycled aggregate, a brief literature review was made, which included analysis of previous laboratory tests of mixes with various percentages of recycled aggregate in the composition, and theoretical studies. The same literature review revealed that it is possible to substitute both fine and coarse aggregates with recycled aggregates in proportions ranging from 0 to 100 % [9-21]. Variations are possible due to various purity levels of recycled aggregate, and various material properties.
The main difference between natural aggregate and recycled aggregate is in their appearance. Unlike natural aggregate, recycled aggregate contains different proportions of the original aggregate and the original cement matrix, and the bond between them, called the old interfacial transition zone. Such a composition results in rough texture and sharp particle edges. The residual mortar content varies from case to case, but literature review reveals that the amount of residual mortar is higher in smaller particles of recycled aggregate, compared to larger ones [16, 17]. Thus, the amount of mortar varies by fraction: a) 25 to 35 % in fraction 16/32 mm, b) about 40 % in fraction 8/16 mm, and c) 60 % in fraction 4/8 mm [17]. Furthermore, the amount of residual mortar affects the density and absorption of recycled aggregate. The density of recycled aggregate is lower compared to natural aggregate [9, 10, 12, 14-16], while the absorption is higher [9, 10, 12, 14-16].
Aggregate occupies most of the volume of concrete but is generally an inert material. Aggregate properties affecting properties of concrete are the grading, particle shape and texture, porosity, density, absorption, and moisture [6]. Aggregate properties are important for the properties of fresh concrete, as well as for its resistance to various aggressive environments, and they also exert a major influence on its modulus of elasticity. As can be seen in literature [9, 10, 12, 14-16], recycled aggregates have slightly worse properties compared to natural aggregates, but they can still be applied quite extensively. Disadvantages such as higher absorption and lower density can be used for internal curing [16, 20], or it is possible to use additional waste materials that improve mixture properties, such as slag, silica fume and fly ash [9, 16]. With careful mix design and proper use of chemical admixtures, recycled aggregate can even be used in self-compacting concrete mixes [13]. Concrete density is directly related to the density of its constituents and, as expected, the density of concrete with recycled aggregate is lower compared to that of ordinary concrete [11, 14, 15, 16, 19, 21]. Replacing 100 % of coarse aggregate with recycled aggregate results in 5 % lower values [14-16], and replacing 100 % of fine aggregate results in 4 % lower values [14]; replacing 100 % of the total natural aggregate with recycled aggregate reduces the density by about 10 % [15, 16]. This is due to lower density of recycled aggregate, higher water absorption, and higher porosity [14, 16]. However, minor differences in the density of fresh mixes are obtained when 50 % of natural aggregate is replaced with recycled aggregate [14, 16].
The amount of water and water-cement ratio have a great influence on mechanical properties. According to [15, 16, 18], to achieve the same consistency as that of ordinary concrete, 5 % more water is required when a coarse recycled aggregate is used, and 15 % more water is required when a fine recycled aggregate is used. This is due to the rough texture of recycled aggregate and the presence of porous mortar, as well as to a higher absorption of recycled aggregate compared to natural aggregate. The demand for more water can be regulated by using saturated dry-surface recycled aggregates, or chemical admixtures [10, 12, 14, 16, 20].
Considerable influence of aggregate properties can be seen in the values of compressive, tensile and flexural strength of concrete [14-17, 20]. It can be seen in [16] that a faster increase in strength is possible by using recycled aggregate, which is due to the presence of non-hydrated cement particles in recycled aggregate. According to the same source, it is also possible to increase or decrease the 28-day compressive-strength value when natural aggregate is substituted. According to [14], a 100 % replacement of natural aggregate with or coarse recycled aggregate results in an average reduction of 30 %, while a 50 % replacement results in an up to 20 % reduction of compressive strength. Fine recycled aggregates have a lower negative impact compared to coarse recycled aggregates. Replacing 30 % of coarse natural aggregate with recycled aggregate reduces compressive strength by 15-17 %, while the same percentage of fine aggregate reduces compressive strength by 10 %. Despite the reduced values of compressive strength compared to ordinary concrete with natural aggregate, it should be emphasized that a compressive strength class of C25/30 [15], C30/37 [20] and values of 40 MPa and 60 MPa [10] can be achieved by using recycled aggregate. The results obtained by testing tensile strength and flexural strength reveal the trend similar to that observed for compressive strength [9, 10, 15, 16, 20]. Tensile strength values are up to 10 % lower when only coarse recycled aggregate is used, while the values are 10-20 % lower when the entire amount of natural aggregate is replaced with recycled aggregate.
The modulus of elasticity of concrete is strongly influenced by aggregates and an expected decrease in its value is proportional to an increase in replacement with recycled aggregates [10,16-18]. Elastic modulus values are on an average 20 % lower with partial replacement, while a 100 % replacement of aggregates with recycled aggregates results in a 60 % decrease [17].

Durability properties are also in line with the above-mentioned trend. The data available in literature point to an increased porosity of recycled aggregate, which reduces the quality of bond between the cement paste and aggregate and the presence of the old interface [18]. While a decrease in permeability was observed in [18] for all types of coarse recycled aggregates, an increase in permeability was observed in [15-17]. The worst results in the capillary absorption testing were obtained when the aggregate was completely replaced with recycled aggregate, while a 25 % replacement of coarse recycled aggregate gave a value approximately equal to that of concrete with natural aggregate [15].
All this shows that some reduction in properties can be expected when using recycled aggregate compared to concrete with natural aggregate, but its use is nevertheless quite feasible. The key to achieve the required properties lies in the design and preparation of materials and in proper quality control.

2. Pilot project "Design and use of concrete with recycled aggregates".

Tender documents for financing construction of a new Day Hospital building in Zadar provide for the award of additional points in the evaluation of tenders, if the tenderers take into account processes related to the reuse (recycling) of construction materials. For these reasons, a pilot project "Design and use of concrete with recycled aggregates" was planned as a part of the detailed design. The pilot project enabled compliance with the Building Act and guaranteed reuse of materials after demolition of the building, and construction of a new building using environmentally friendly raw materials and secondary materials, all in accordance with the 7th basic requirement for buildings [22].
The detailed design called for demolition of the existing building at the site of the new building (Figure 1). The raw material generated during this demolition was used in the preparation of concrete with recycled aggregate. Thus a part of the new reinforced-concrete structure was built using recycled aggregate concrete. According to the design, this recycled aggregate concrete was destined for erection of internal reinforced-concrete walls on the third floor in axes D and G, as shown in Figure 2. It was established that these walls belong to the exposure class XC1, for which only the basic compressive strength requirement is prescribed. According to structural analysis, the minimum compressive strength of concrete used for these walls was set to C/20/25, which is in accordance with the compressive strength requirements and the requirements specified in HRN EN 1998-1 [23] for ductility class DCM.
The detailed design contains requirements for components, aggregates in particular, as well as requirements for concrete composition, while also defining tests for aggregates, and requirements for the fresh and hardened concrete, the aim being to confirm compliance of recycled

Figure 1. Old infectious disease building scheduled for demolition at Zadar General Hospital

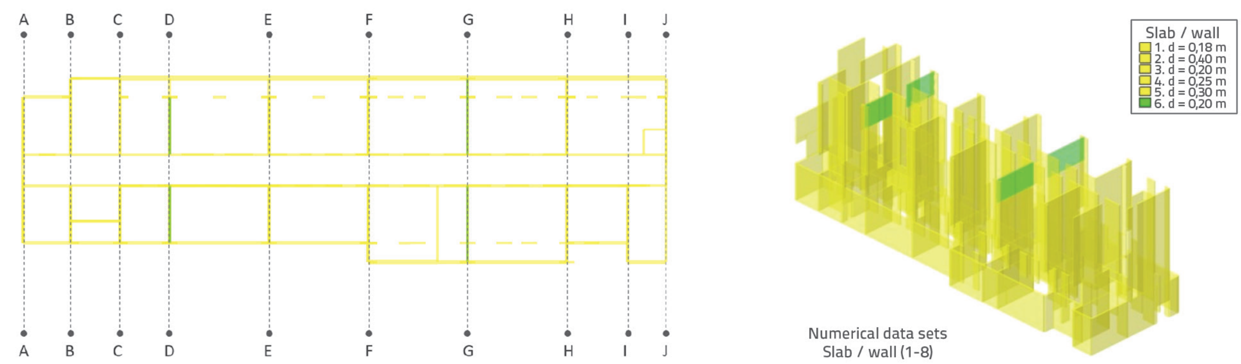

Figure 2. Plan view of the third floor and 3D model of the structure, with marks showing walls to be made of recycled-aggregate concrete.

Figure 3. Existing building demolition waste

Figure 4. Separated recycled aggregate placed at a temporary stockpile

aggregate concrete with the design criteria. A timeline of activities with implementation deadlines is provided along with a cost estimate for all pilot-project works that the contractor should perform during demolition of the old building and construction of the new one (demolition, waste separation, removal, separation of reinforcement, crushing, division of aggregates into fractions, mix design, testing, and construction). All pilot-project activities (preparation, implementation, and monitoring) are specified in the detailed design, and they served as basis for definition of project supervision and for procurement of construction permit.

3. Materials and methods

The following materials were used for concrete production: cement CEM II / BM (S- LL) 42.5 N, manufactured by Cemex doo, crushed aggregate from KOSMALJ-Zapužane plant (0/4 mm, 8/16 mm), coarse recycled aggregate (16/32 mm), superplasticizer ISOFLOW 8501, manufactured by Cemex doo, and tap water.

3.1. Recycled aggregate

The concrete originating from beam lintels, horizontal ring beams, and foundations, was used in the production of recycled aggregate. This concrete was mostly unreinforced concrete characterized by low compressive strength (≤ C20/25). The existing-building demolition design called for selective demolition with separation of various types of waste materials. This involved demolition of building elements in correct sequence, starting with the removal of craftsmen's elements (furnishings, joinery, ceilings, cladding, etc.), and continuing with secondary or non-structural elements (secondary structures, masonry infills, partitions, and all layers of floors and ceilings up to structural elements). In this way, all elements that are not part of the load-bearing structure were removed, which facilitated removal and sorting of collapsed structural elements, Figure 3. The material thus prepared was then crushed to the required size by mechanical crushing, and separated to form a 16/32 mm fraction, Figure 4.

The detailed design called for detailed testing of coarse recycled aggregate (Table 4), while properties of natural (crushed) aggregate required for concrete design were provided by the manufacturer. The coarse recycled aggregate test results (Table 4) show that all values are in accordance with the criteria specified in HRN EN 12620 [8]. This confirms that the recycled aggregate obtained from the demolition of the existing general hospital building in Zadar can be used for construction of the new building.

The density of crushed aggregate in saturated surface-dry state is 2.67 kg/dm^3, while the same value for recycled aggregate is 2.48 kg/dm^3. The lower density of recycled aggregate is due to the presence of mortar and other impurities on the surface of recycled aggregate. The recycled aggregate can be declared as RC90, (Table 1), Type A (Table 2), and thus it can be used for the exposure class XC1 in the proportion of no more than 30 %.

The results obtained by testing particle size distribution of crushed aggregate (0/4 mm, 8/16 mm, 16/32 mm) and recycled aggregate (16/32 mm) are shown in Figure 5. This graphical representation of particle size distribution test results shows that the recycled aggregate curve does not deviate much compared to the curve of crushed aggregate. The crushed aggregate fraction 16/32 mm was completely replaced by recycled aggregate of the same fraction. This

Table 4. Results obtained by testing physical and chemical properties of coarse-grained recycled aggregate according to HRN EN 12620 [8]

Property	Test method	Results		Acceptance criterion	Criterion satisfied
Particle size distribution	HRN EN 933-1 [24]	Figure 5.		To be declared	Not applicable
Fines content	HRN EN 933-1 [24]	1.6 g		To be declared	Not applicable
Flakiness index	HRN EN 933-1 [24]	4 %	FI_{15}	≤ FI_{15}	YES
Resistance to fragmentation	HRN EN 1097-2 [25]	34	LA_{35}	≤ LA_{50} ili SZ_{32}	YES
Particle density	HRN EN 1097-6 [26]	2380 kg/m³		≥2100 kg/m³	YES
Water absorption	HRN EN 1097-6 [26]	3.75 %		To be declared	Not applicable
Acid-soluble sulphate content	HRN EN 1744-1 [27]	0.2 %	$AS_{0.2}$	$AS_{0.2}$	YES
Water-soluble chloride ion content	HRN EN 1744-1 [27]	0.001 %		To be declared	Not applicable

means that the share of recycled aggregate in the total volume of aggregate is 22 %.

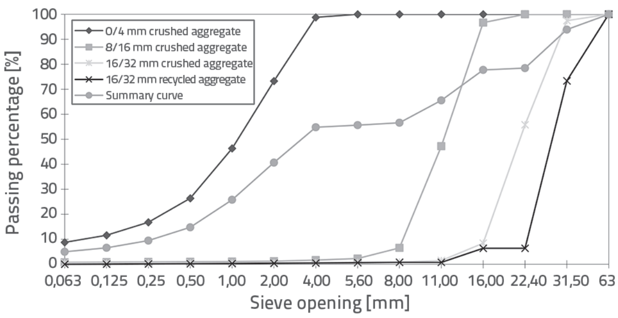

Figure 5. Graphical representation of results obtained by testing particle size distribution of crushed and recycled aggregate

3.2. Test methods

The experimental programme for testing fresh and hardened concrete containing recycled aggregates is divided into two phases: a) preparation of trial mixes and b) construction of walls. Trial mixes were prepared in the laboratory of the Department of Materials of the Faculty of Civil Engineering, University of Zagreb, and in the concrete plant of the company Cemex d.o.o. in Zadar. After trial mixes produced in concrete plant reached the required compressive strength at 28 days, the construction of the third-floor walls of the new Zadar Day Hospital building was started using concrete of the same composition. Fresh concrete properties were tested at all stages, while compressive strength tests on hardened concrete were conducted at the age of 2, 7, and 28 days. Exceptionally, the compressive strength for the mix BRA1 (which was prepared in the laboratory) was tested only at the ages of 2 and 7 days at the contractor's request in order to speed up construction work. Using theoretical functions for predicting an increase in compressive strength [36], as based on compressive strength laboratory tests conducted at 2 and 7 days of age, it was concluded that the expected compressive strength at 28 days meets project requirements. That is why this was immediately followed by preparation of trial mix at concrete plant. In addition, the modulus of elasticity, capillary absorption, water permeability, and drying shrinkage, were tested in the second phase. Test standards and specimen dimensions are shown in Table 5. All tests were performed on three specimens.

3.3. Concrete mix design and preparation of specimens

Composition of concrete is given in Table 6. A total of 4 mixes were prepared: a) mix BRA1 in laboratory, b) mix BRA2 at the concrete plant, c) mix BRA3 for construction of walls, and d) ordinary concrete mix OB as a reference mix. All mixes were prepared using the same concrete composition. The only difference is that the mixes marked BRA contain recycled aggregate instead of the 16/32 mm crushed aggregate fraction. The mixing and sample preparation procedure used in laboratory differed from the procedure used at the concrete plant. Under laboratory conditions, the total aggregate and

Table 5. Test methods for fresh and hardened concrete

Test method	Norm	Sample dimensions
Slump test	HRN EN 12350 – 2:2009 [28]	-
Density	HRN EN 12350 – 6:2009 [29]	-
Air content - Pressure methods	HRN EN 12350 – 7:2009 [30]	-
Compressive strength	HRN EN 12390 – 3:2009 [31]	150 x 150 x 150 mm
Modulus of elasticity	HRN EN 12390 – 13:2013 [32]	d/h = 10 x 200 mm
Penetration of water under pressure	HRN EN 12390 – 8:2019 [33]	150 x 150 x 150 mm
Capillary absorption	HRN EN 13057:2003 [34]	d/h = 10 x 50 mm
Drying shrinkage	HRN EN 12390 – 16:2019 [35]	100 x 100 x 400 mm

Table 6. Concrete composition

Component	Cement [kg]	Water [l]	Superplasticizer (0.36 % m_c, l)	Aggregate [kg]		
				0/4 mm	8/16 mm	16/32 mm
	320	180	1,15	1029	412	398

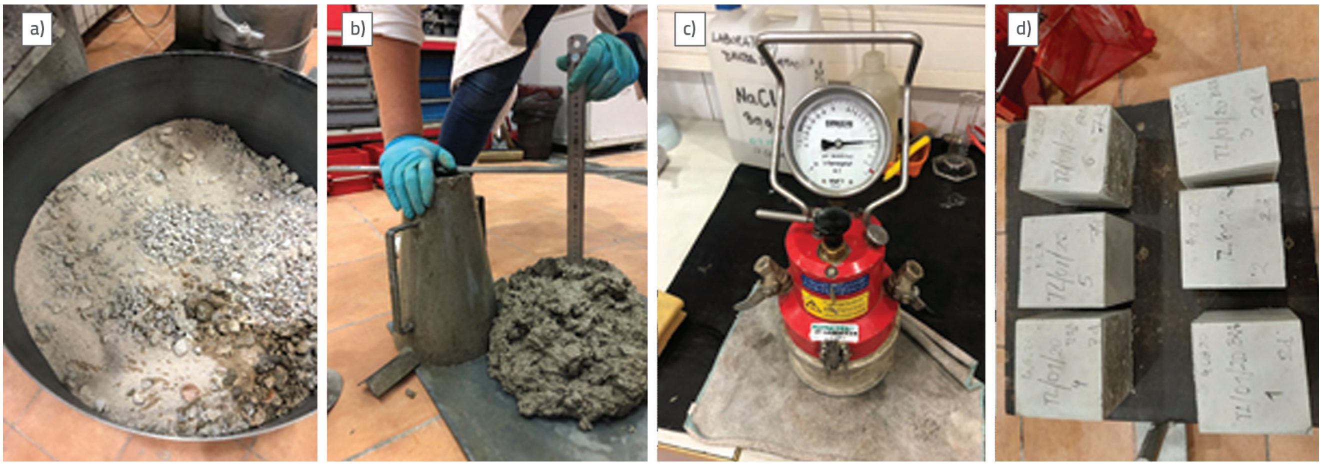

Figure 6. Preparation of recycled aggregate concrete in laboratory: a) aggregate, b) consistency test, c) pore content, d) specimens for compressive strength test

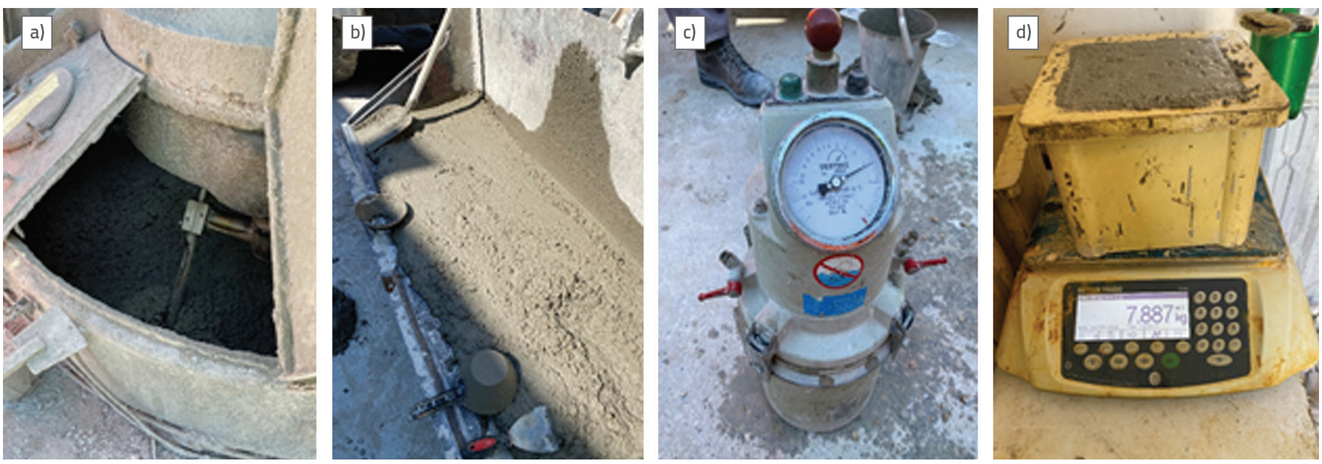

Figure 7. Preparation of fresh concrete with recycled aggregate: a) fresh concrete, b) sampling, c) testing of porosity, d) determination of density

half of the calculated amount of water were first added to the mixer (Figure 6). After two minutes of mixing to ensure water absorption into the aggregate, a two-minute break was taken and the remaining ingredients were added. Mixing was then continued and superplasticizer was added. The concrete was placed in the moulds while it was vibrated on a vibrating table. After 24 hours, the specimens were demoulded and stored in a humid chamber at a temperature of 20 ± 2 ° C and at relative humidity of 95 % until the age of 7 days.

At the concrete plant, all ingredients were automatically proportioned, except for the recycled aggregate and superplasticizer. The ingredients were added simultaneously, then stirred for 2 minutes. After preparation, the concrete was delivered by loader to the front of the field laboratory, where samples were taken and concrete was placed into moulds under vibration on the vibrating table, Figure 7.

4. Results and discussion

4.1. First phase - trial mixes

The production of concrete mixes with recycled coarse aggregates was carried out in the first phase, i.e. first in laboratory of the Department of Materials of the Faculty of Civil Engineering in Zagreb and then at the concrete plant. Greater tolerances of the device for automatic proportioning of constituents at the concrete plant resulted in a higher content of the 0/4 mm fraction of crushed aggregate, i.e. the content was higher by 4.3 % compared to the laboratory mix. Other constituents were proportioned according to the designed concrete composition. Test results are presented in Table 7. For the BRA2 mix prepared at the concrete plant, the slump consistency value was by 6 % higher than the same value for the BRA1 mix prepared in laboratory. However, both mixes belong to the slump class S4 (160 - 210 mm).

Table 7. Test results for recycled aggregate concrete, in laboratory and at the concrete plant

Property		1st phase - initial mixes		2nd phase - wall construction	
		BRA1 laboratory	**BRA2** concrete plant	**BRA3** concrete plant	**OB** concrete plant
Slump [mm]		160	170	170	170
Air content [%]		2.5	1.9	2.5	2.4
Density [g/cm^3]		2355	2337	2290	2363
Temperature [°C]		25.4	29.3	20.2	20.4
Compressive strength [MPa]	2 days	25.28 ± 0.52	19.87 ± 0.46	11.63 ± 0.46	14.77 ± 0.58
	7 days	33.75 ± 0.88	27.63 ± 0.81	22.59 ± 1.45	22.85 ± 0.71
	28 days	-	32.54 ± 0.11	30.09 ± 0.10	30.62 ± 0.43
Modulus of elasticity [GPa]		-	-	28.82 ± 1.9	30.80 ± 3.8
Water penetration depth [mm]		-	-	45 ± 8	44 ± 7

The air content in fresh concrete is by 24 % lower in the BRA2 mix produced at the concrete plant than in the BRA1 mix. The lower air content may be due to higher percentage of fine particles in the mix because of automatic placement of aggregates, but it may also be due to shorter mixing time at the concrete plant, as the percentage of entrapped air correlates with mixing time. This behaviour is consistent with assumptions from literature [18, 21]. The temperature of fresh concrete depends on environmental conditions at the time of pouring. In laboratory, the conditions were controlled and the material was stored at 20 °C for 24 hours before mixing. On the other hand, the temperature reached 34°C on the day the BRA2 mix was mixed in Zadar. The increase in outdoor temperature was reflected in the temperature of the constituents and fresh concrete but was still within the limits specified in HRN EN 13670 [37]. Fresh concrete density is by 1 % lower for the BRA2 mix compared to the BRA1 mix, and the minimal difference obtained can be neglected.

Compressive strength values for BRA2 at 2 and 7 days of age were on an average by 21 % and 18 % lower than the compressive strength values of BRA1 prepared in laboratory (Table 7). It should be noted that such results were partly expected due to the difference in conditions between the laboratory and the concrete plant. It is therefore recommended that the test mixes should always be prepared in the concrete plant as well.

Table 8. Conformity criteria for compressive strength of BRA2 mix in accordance with HRN EN 206 [7]

Test results		Criteria for C20/25	
f_{ci}	32.42 MPa	21 MPa	**YES**
f_{cm}	32.54 ± 0.11 MPa	29 MPa	**YES**
Global criteria		**YES**	

At 28 days of age, compressive strength was determined only for the BRA2 mix produced at the concrete plant. The measured strength was used to evaluate compliance with the compressive strength criteria for the initial concrete type testing according to HRN EN 206 [7], Table 8. Based on the tests performed, it can be concluded that the proposed concrete composition with recycled aggregate, given in Table 6, can be declared as C20/25, which confirms that it meets requirements specified in the detailed design.

4.2. Second phase - Placing concrete with recycled coarse aggregate for walls

A coarse recycled aggregate mix was used in this phase as its compliance with the detailed design had been confirmed in previous phases. In addition, a reference mix of ordinary concrete (OB) was prepared to evaluate contribution of coarse recycled aggregate to concrete properties. The specimens were prepared during construction of the 3rd floor walls of the Zadar Day Hospital. Fresh concrete was taken from mixer to test fresh concrete properties and to prepare specimens for testing hardened concrete properties before the recycled aggregate concrete was delivered to the site. The test results are shown in Table 7.

Figure 8. Casting recycled aggregate concrete for 3rd floor walls of Zadar Day Hospital.

In general, the use of recycled aggregate contributes to a lower concrete density value because the density of recycled aggregate is lower compared to that of natural aggregate [11, 14, 15, 19, 21]. When comparing the properties, it was established that

the density of fresh concrete BRA3 was by 3 % lower compared to the reference mix OB, which could be related to the initially lower density of recycled aggregate. An average reduction in density for concrete with 100 % coarse recycled aggregate is 5 %, while the change in density is negligible when the percentage of recycled aggregate is lower than 50 % [14-16, 19, 21].
On the other hand, workability of concrete increases when recycled aggregate in saturated, surface-dry state is used for production. However, it should be noted that the use of recycled aggregate under this condition of moisture is not suitable for ordinary concrete production, and so lower workability of concrete with recycled aggregate is expected due to higher absorption. According to [15], to achieve the same consistency as ordinary concrete, 5 % more water is required when coarse recycled aggregate is used, and 15 % more water is required when fine recycled aggregate is used. In this case, to achieve the same consistency class for mixes with recycled aggregate, it was necessary to increase the superplasticizer content by 0.07 % of the cement weight (m_c) compared to the mix with crushed aggregate. This is directly related to mortar content in recycled aggregate, i.e., to the proportion of new to old interface.
Compressive strength values of concrete with recycled coarse aggregate (BRA3) at 2, 7 and 28 days of age are on an average by 21 %, 1 % and 2 % lower than compressive strength values of ordinary concrete (OB). Although a slower increase in compressive strength was obtained for concrete with recycled aggregate, the values of compressive strength at 28 days can be considered the same, Table 7.
Similar behaviour was observed when testing the modulus of elasticity of concrete, where the value of modulus of elasticity for concrete with recycled material is on an average by 6 % lower compared to ordinary concrete. The modulus of elasticity depends on compressive strength, volume fraction of aggregate, and elastic modulus of aggregate. It is expected that a decrease in compressive strength and lower stiffness and density of aggregate will decrease the value of elastic modulus [10, 12, 16-18]. Studies show that modulus of elasticity is by about 15 % lower compared to reference mix when 30 % of aggregate is replaced with recycled aggregate [17].
Durability test results show higher permeability, i.e. water absorption, of concrete with recycled aggregate compared to ordinary concrete, as shown in Figure 9. Water absorption of the BRA3 mix at 24 hours was by 15 % higher compared to the OB mix. Previous studies have shown that an increased porosity of the recycled coarse aggregate can reduce quality of the bond between the cement paste and aggregate in the interface zone, resulting in an increased permeability of concrete [18]. However, the values obtained also depend on the w/c ratio. Thus, the results presented in [15-17] show increased permeability, while reduced permeability is reported in [18] for all types of recycled aggregate compared to concrete with natural aggregate. It should also be noted that the water permeability test shows that the mixes BRA3 and OB belong to the same water permability class, Table 7.

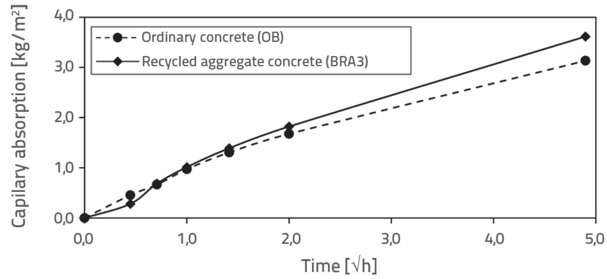

Figure 9. Graphical representation of capillary absorption tests for ordinary concrete and recycled aggregate concrete

A graph showing the drying shrinkage test results over 90 days is given in Figure 10. The graph shows slightly higher volume changes in concrete with recycled aggregate (BRA3) compared to ordinary concrete (OB). After 107 days of measurement, the drying shrinkage is by 17 % higher than that of the reference mix OB. Such an increased shrinkage is due to the presence of mortar on recycled aggregate and the associated higher water absorption. This result indicates higher shrinkage of the BRA3 mix compared to the literature data. The data suggest that a 15 to 40 % increase in shrinkage occurs when 100 % of natural coarse aggregate is replaced with recycled aggregate, while the shrinkage of ordinary concrete and recycled aggregate concrete remains similar when 30 % of the natural coarse aggregate is replaced, [17].

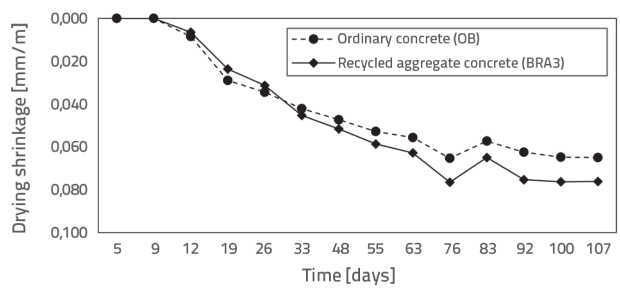

Figure 10. Graphical representation of drying shrinkage results for ordinary concrete and recycled aggregate concrete

5. Conclusion

The case study presented in this paper is a positive example of the use of all basic requirements for construction works in the detailed design, such as requirements relating to mechanical resistance and stability, and requirements ensuring sustainable use of natural resources. The progress of society goes hand in hand with continuous development of the construction sector, which for years has shown, through successful examples, positive sides of transforming construction waste into products with new value.
Following comparison between the recycled aggregate concrete and the ordinary-concrete reference mix with crushed aggregate, the following results were obtained:
- lower workability of fresh mix due to higher absorption of recycled aggregate compared to crushed aggregat

- concrete density is reduced by 3 %, which is directly related to lower density of recycled aggregate compared to crushed aggregate
- although there is a slower increase in compressive strength for concrete specimens with recycled aggregate, the 28-day values differ by 2 % only
- elastic modulus of concrete specimens with recycled aggregate is on an average by 6 % lower when compared to concrete with crushed aggregate
- in the drying shrinkage test, after 107 days, 17 % higher values were obtained compared to those for concrete with crushed aggregate
- durability properties are reduced, i.e. up to 15 % higher capillary water absorption was observed for concrete specimens with recycled aggregate compared to crushed aggregate, but it should be emphasized that both types of concrete belong to the same class of water permeability.

Multiple sustainability-related benefits of this approach do not require much explanation:
- reduced consumption of natural resources,
- reduced need for disposal to landfills
- on-site reuse.

The presented research on the use of recycled materials in concrete and the use of concrete with recycled aggregates in the construction of new buildings can be used in the reconstruction of buildings damaged by an earthquake in 2020. The paper [38] details the number of damaged buildings and the extent of damage, which shows the future need for a large amount of construction material. Therefore, construction waste generated from the demolition of damaged buildings or their parts could be the answer to the significant demand for basic components for concrete production, but also the answer to reduce of the pressure on already overfilled landfills. In addition to the use of recycled material, consideration should also be given to the use of range of by-products and waste materials which, according to [39] can be used to develop different types of alternative binders for concrete.

All this contributes to development of the society that will provide a dignified legacy for future generations, the society that knows how to deal with huge amounts of waste generated by earthquakes that devastated Croatia last year. Therefore, the case study presented in this paper is extremely important, primarily because it shows that simple testing and quality control methods can ensure reuse of construction waste.

The tests carried out during construction of the new building of the Zadar Day Hospital, as part of the pilot project "Design and use of concrete with recycled aggregates", confirm that recycled aggregate concrete with properties equivalent to those of ordinary concrete can be used, if prevailing standards and regulations for recycled aggregates are complied with, and if the origin of the recycled aggregates is known. On the basis of tests carried out in the scope of this study, it can be concluded that, under the given durability conditions, the use of recycled concrete as partial substitute for natural aggregate is justified from environmental, economic, and operational points of view. However, it should be noted that properties of specimens prepared in the laboratory differ greatly from properties observed at the concrete plant, especially when concrete was sampled during construction. This shows the importance of performing quality control for all components, but also for the final product, in order to eliminate possible deviations.

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REFERENCES

[1] Bjegović, D., Serdar, M., Rukavina, M.J., Baričević, A.: Istraživanja kriterija održivosti armiranog betona, GRAĐEVINAR, 62 (2010) 10, pp. 931-940

[2] Zakon o održivom gospodarenju otpadom, NN 94/13 (98/19), Narodne novine, 2019.

[3] Kufrin, J.: Pregled podataka o gospodarenju građevnim otpadom u 2018. godini, Ministarstvo zaštite okoliša i energetike, Zavod za zaštitu okoliša i prirode, 2019.

[4] Pravilnik o katalogu otpada, NN 90/15, Narodne novine, 2015.

[5] Vermeulen, J.: Protokol EU-a za gospodarenje građevnim otpadom i otpadom od rušenja, Europska Komisija, 2016.

[6] Bjegović, D., Štirmer, N.: Teorija i tehnologija betona, Građevni fakultet Sveučilišta u Zagrebu, 2015.

[7] Hrvatski zavod za norme: Beton - Specifikacija, svojstva, proizvodnja i sukladnost; HRN EN 206:2016m, (EN 206:2013+A1:2016)

[8] Hrvatski zavod za norme: Agregati za beton; HRN EN 12620:2008, (EN 12620:2002+A1:2008)

[9] Damdelen, O.: Investigation of 30% recycled coarse aggregate content in sustainable concrete mixes, Construction Building Materials, 184 (2018), pp. 408–418, doi:10.1016/j.conbuildmat.2018.06.149.

[10] Butler, L., West, J.S., Tighe, S.L.: Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength, Construction Building Materials, 47 (2013), pp. 1292–1301, doi:10.1016/j.conbuildmat.2013.05.074.

[11] Rashid, K., Rehman, M.U., De Brito, J., Ghafoor, H.: Multi-criteria optimization of recycled aggregate concrete mixes, Journal of Cleaner Production, (2020), pp. 276, doi:10.1016/j.jclepro.2020.124316.

[12] Tahar, Z., El Abidine, T.T., Kadri, E.H., Bouvet, A., Debieb, F., Aggoun, S.: Effect of cement and admixture on the utilization of recycled aggregates in concrete, Construction Building Materials, 149 (2017), pp. 91–102, doi:10.1016/j.conbuildmat.2017.04.152.

[13] Larsen, O., Naruts, V., Aleksandrova, O.: Self-compacting concrete with recycled aggregates, Materials Today: Proceedings, 19 (2019), pp. 2023–2026, doi:10.1016/j.matpr.2019.07.065.

[14] Bidabadi, M.S., Akbari, M., Panahi, O.: Optimum mix design of recycled concrete based on the fresh and hardened properties of concrete, Building Engineering, 32 (2020), doi:10.1016/j.jobe.2020.101483.

[15] Berredjem, L., Arabi, N., Molez, L.: Mechanical and durability properties of concrete based on recycled coarse and fine aggregates produced from demolished concrete, Construction Building Materials, 246 (2020), doi:10.1016/j.conbuildmat.2020.118421.

[16] Verian, K.P., Ashraf, W., Cao, Y.: Properties of recycled concrete aggregate and their influence in new concrete production, Resources, Conservation & Recycling, 133 (2018), pp. 30–49

[17] Kovač, D.: Beton od recikliranog agregata, Magistarski rad, Građevni fakultet Sveučilišta u Zagrebu, 2008.

[18] Sironić, H.: Primjena recikliranih materijala u proizvodnji betona, Magistarski rad, Građevni fakultet Sveučilišta u Rijeci, 2010.

[19] Lavado, J., Bogas, J., de Brito, J., Hawreen, A.: Fresh properties of recycled aggregate concrete, Construction Building Materials, 233 (2020), doi:10.1016/j.conbuildmat.2019.117322.

[20] El-Hawary, M., Al-Sulily, A.: Internal curing of recycled aggregates concrete, Journal of Cleaner Production, 275 (2020), doi:10.1016/j.jclepro.2020.122911.

[21] Silva, R.V., De Brito, J., Dhir, R.K.: Fresh-state performance of recycled aggregate concrete: A review, Construction Building Materials, 178 (2018), pp. 19–31, doi:10.1016/j.conbuildmat.2018.05.149.

[22] Zakon o gradnji, NN 153/13 (125/19), Narodne novine, Zagreb, 2019.

[23] Eurokod 8: Projektiranje potresne otpornosti konstrukcija - 1. dio: Opća pravila, potresna djelovanja i pravila za zgrade; HRN EN 1998-1:2011, (EN 1998-1:2004+AC:2009)

[24] Hrvatski zavod za norme: Ispitivanje geometrijskih svojstava agregata - 1. dio: Određivanje granulometrijskog sastava - Metoda sijanja; HRN EN 933-1, (EN 933-1:2012)

[25] Hrvatski zavod za norme: HRN EN 1097-2:2011 Ispitivanja mehaničkih i fizikalnih svojstava agregata - 2. dio: Metode za određivanje otpornosti na drobljenje, (EN 1097-2:2010)

[26] Hrvatski zavod za norme: HRN EN 1097-6:2004 Ispitivanja mehaničkih i fizikalnih svojstava agregata - 6. dio: Određivanje gustoće i upijanja vode, (EN 1097-6:2000+AC:2002)

[27] Hrvatski zavod za norme: HRN EN 1744-1:2012 Ispitivanja kemijskih svojstava agregata - 1. dio: Kemijska analiza, (EN 1744-1:2009+A1:2012)

[28] Hrvatski zavod za norme: Ispitivanje svježega betona - 2. dio: Ispitivanje slijeganjem; HRN EN 12350-2:2019, (EN 12350-2:2019)

[29] Hrvatski zavod za norme: Ispitivanje svježega betona - 6. dio: Gustoća; HRN EN 12350-6:2019, (EN 12350-6:2019)

[30] Hrvatski zavod za norme: Ispitivanje svježega betona - 7. dio: Udio pora - Tlačne metode; HRN EN 12350-7:2019, (EN 12350-7:2019)

[31] Hrvatski zavod za norme: Ispitivanje očvrsnuloga betona - 3. dio: Tlačna čvrstoća ispitnih uzoraka; HRN EN 12390-3:2019, (EN 12390-3:2019)

[32] Hrvatski zavod za norme: Ispitivanje očvrsloga betona - 13. dio: Određivanje sekantnog modula elastičnosti pri tlaku; HRN EN 12390-13:2013, (EN 12390-13:2013)

[33] Hrvatski zavod za norme: Ispitivanje očvrsnuloga betona - 8. dio: Dubina prodora vode pod tlakom; HRN EN 12390-8:2019, (EN 12390-8:2019)

[34] Hrvatski zavod za norme: Proizvodi i sustavi za zaštitu i popravak betonskih konstrukcija - Ispitne metode: Određivanje otpornosti na kapilarno upijanje; HRN EN 13057:2003, (EN 13057:2002)

[35] Hrvatski zavod za norme: Ispitivanje očvrsnuloga betona - 16. dio: Određivanje skupljanja betona; HRN EN 12390-16:2019, (EN 12390-16:2019)

[36] Eurokod 2: Projektiranje betonskih konstrukcija - Dio 1-1: Opća pravila i pravila za zgrade; HRN EN 1992-1-1:2013, 2010, (EN 1992-1-1:2004+AC:2010)

[37] Hrvatski zavod za norme: Izvedba betonskih konstrukcija; HRN EN 13670, (EN 13670:2009)

[38] Šavor Novak, M., Uroš, M., Atalić, J., Herak, M., Demšić, M., Baniček, M., Lazarević, D., Bijelić, N., Crnogorac, M., Todorić, M.: Zagreb earthquake of 22 March 2020 – preliminary report on seismologic aspects and damage to buildings, GRAĐEVINAR, 72 (2020) 10, pp. 843-867, doi: https://doi.org/10.14256/JCE.2966.2020

[39] Serdar, M., Bjegović, D., Štirmer, N., Pečur, I.B.: Research challenges for broader application of alternative binders in concrete, GRAĐEVINAR, 71 (2019) 10, pp. 877-888, doi: https://doi.org/10.14256/JCE.2729.2019