SVEUČILIŠTE U ZAGREBU
GRAĐEVINSKI FAKULTET
UNIVERSITY OF ZAGREB
FACULTY OF CIVIL ENGINEERING

Construction materials roadmap for R&D

Dubravka Bjegović[1], Ivana Banjad Pečur[1], Nina Štirmer[1], Marijana Serdar[1], Bojan Milovanović[1], Marija Jelčić Rukavina[1], Ana Baričević[1]
[1] University of Zagreb, Faculty of Civil Engineering, Department of materials, Croatia

Abstract:

Research activity within the Civil Engineering Materials field in the Materials Department at Civil Engineering Faculty University of Zagreb was in progress through several themes under the common interest – sustainable development. Sustainable development is one of the major issues of modern society, highly endangered by industrialization and technological development. Within this area, research includes material response to environmental processes; the interaction between environment, material properties and degradation processes; in-service performance of materials; low-embodied-energy construction materials, and the development of novel micro- and macro- characterisation techniques to study hybrid materials such as hybrid micro fiber concrete. The research comprises both theoretical and experimental studies, the latter including micro-scale examination, full-scale testing and field studies. An overview of possible actions that can be employed in concrete technology in order to upgrade concrete industry and create one that is environmentally more friendly and sustainable is given. Some of the actions include using of blended cements and new types of binders, recycled aggregate from construction and demolition waste, industrial waste or from end-of-life tyres, prolongation of service life by prescribing, controlling and assuring durability in design, construction and exploitation phase of concrete structure. The benefits of given actions are highlighted through presentation of experimental results obtained on the existing scientific projects in the area of sustainable development.

Key words: CO2 emission, recycling, waste tyres, corrosion, fire resistance, durability, energy efficiency

1 Introduction

The today industry is highly dependent on the health of the construction sector, which spans residential, commercial and industrial segments. The fastest-growing market in the last couple of decades has been China, although that market has begun slowing down in 2012. In North America and Western Europe, the fast-growing segment of the building materials market has been green building materials: a segment which is expected to reach $250 billion over the next 5-7 years. While there is a degree of fuzziness in the definition of what makes a building material green, it typically means that the product requires fewer resources to produce, reduces building energy needs and water consumption, or is manufactured with post-consumer or post-industrial product content. Environmental protection and energy saving are crucial problems in all fields of human activities, especially in production and industry. Sustainable development has become one of the most evident solutions in order to prolong the existence of clean and healthy environment.

The 1992 Earth Summit in Rio de Janeiro defined sustainable development as economic activity that is in harmony with the earth's ecosystem [1]. The best way to ensure sustainable development would be to reconcile human needs with the capacity of the planet to cope with the consequences of human activities, or in other words to take from the earth as little as possible natural resources and return to the earth as little as possible waste. Concrete industry today, is largest consumer of natural resources and one of the largest waste producers. That is why there is a need of upgrading concrete industry and creating one that is environmentally friendly and sustainable. Yearly around 750 million m^3 of concrete is being produced in Europe, which is equivalent to consumption of around 4 tonnes of concrete per EU citizen [2]. Even though, compared to other building materials, concrete is considered to be environmentally friendly, its constituents and production technology are not. Postulates of sustainability in construction industry are most definitely: lowering CO_2 emission, with the use of by-products of other industry as substitutions of Portland cement; conservation of natural resources, with the use of recycled materials instead of crushed stone for aggregate and designing, constructing and maintaining more durable concrete structures.

Researchers in the field of Civil Engineering materials are addressing a number of these areas through monitoring the performance of concrete in its service environments through the development of durability indicators for concrete and instrumentation at full-scale. Field studies are also aimed at developing remote interrogation of embedded sensors utilising mobile technology. Other areas include the development of cementitious systems with multifunctional capabilities (smart materials) to allow the material to simultaneously provide both structural and non-structural applications and current research focuses on hybrid recycled fibre from tyres as component for reinforced PC concrete composites and the use of recycled aggregate for development of energy efficient precast façade panels. The benefits of given actions are highlighted through presentation of experimental results obtained on the existing scientific projects in the area of sustainable development which are being performed at Department of Materials at the University of Zagreb, Faculty of Civil Engineering.

Basis for sustainability in concrete industry is in three primary aspects as demonstrated with Figure 1.

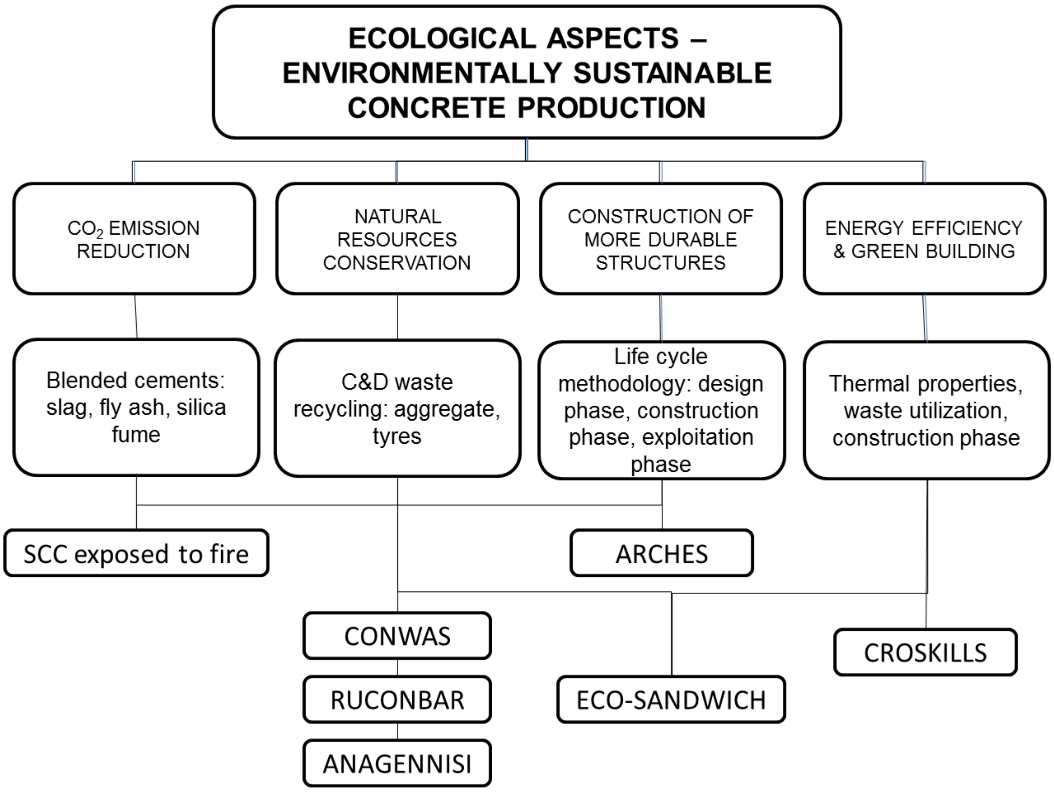


Figure 1. Construction materials roadmap for R&D

2 CO_2 emission REDUCTION

Nowadays, the world consumption of cement is more than 2.5 billion tonnes annually [1] and it is expected that this number will rise with the industrialization of developing countries. In Croatia, there is still a growth trend of CO_2 emission. In year 2006, direct CO_2 emission from cement industry was around 2.5 million tonnes, which is compared to year 1990 growth of 51 %. In year 2006, specific CO_2 emission was estimated to be 850 kg CO_2/t of clinker or 700 kg CO_2/t of cement. That means that in Croatia cement industry causes around 8-9 % of total CO_2 emission [3, 4]. Clinker substitution is a promising solution as it is a low-cost option that has not yet been used to the greatest possible extent, and, as such, still has great potential [4]. The most common supplementary materials are fly ash, granulated blast furnace slag, silica fume and limestone. However, in order to create market acceptance, the properties of these binding materials have to be comparable with Portland cement [5]. Experimental research performed on concrete mixtures with quaternary-blended cements shows that the substitution of cement with by-products of other industries can have a positive influence on concrete durability properties (penetrability of fluids and ions, early age cracking) [6, 7]. Even though a single type of mineral admixture can have different influence on a specific concrete property, synergic influence of mix of mineral can be achieved. Therefore, the mix of binders in quaternary blended cement can be designed in a way that the benefits of each added mineral admixture are utilised [8]. In this area comes also the work on SPIN project. SPIN is acronym of Expert network for innovative, clean and safe cement and concrete technology, one EU project under the ACP Science and Technology Programme. SPIN is a consortium of 11 academic and non-academic institutions from six African and three European Union countries (Burundi, Croatia, DR Congo, Germany, Mozambique, Netherlands, Rwanda, South Africa, Tanzania, and Uganda) with a special focus on R&D in the area of Cement, Concrete Technology, and Concrete Construction.

Africa is a promising continent for the construction industry. The population is estimated to have exceeded one billion people in 2009 of which almost 40 % live in urban areas. Sub-Saharan Africa is populated by more than half a billion people. Rapid urbanization creates challenges for the urban development, especially in the areas of housing, infrastructure, and service delivery. In many countries, markets emerge rapidly, and the growing economies demand for rapid construction activities, since investments in infrastructure, housing, roads, railways, power supply, dams and water pipelines are critical to the well-being of the population. This situation indicates that, cement and concrete will play a major role in the future construction technology in Africa, despite the fact that it does not have a long lasting tradition all over most of the continent. Africa is rich in natural resources for the production of mineral binder systems. However, many sub-Saharan African countries exhibit challenging boundary conditions which have to be well understood in order to use cement and concrete technologies in a sustainable and reasonable way.

An overall objective of the project is to establish an international cooperation network of experts and researchers that will strengthen links between Europe and Africa in the field of civil engineering, with a particular emphasis on the development and application of existing knowledge and applied research in technologies relating to cement and concrete industry. One of the main goals of the present day world is sustainability, and this goal has been addressed on this project in several areas, including environmental protection, health care, energy savings, alternative sources of energy, development, and abatement of poverty. Several papers are published during the project work and can be found at www.spin.bam.de.

Another replacement for cement is mineral admixture called metakaolin. Metakaolin is obtained under controlled process as primary product, from kaolin clay in rotary kilns at about 800℃. The research c arried out up to the present showed a positive influence of metakaolin on mechanical and durability properties of hardened concrete. However, these researches have not covered the influence of curing regimes on the properties of concrete with metakaolin admixture.

The research performed on Department of Materials showed that decreased amount of CH due to formation of secondary CSH with presence of metakaolin assures increase in 28-day compressive strength, and an improvement in durability properties. But as expected, concretes with or without metakaolin cured in ambient conditions have poorer durability properties than those cured in laboratory conditions. Regardless to the curing regime used, 15 % of metakaolin exhibits good test results of chloride diffusion coefficient. Since it is indicative that the use of high performance concrete containing metakaolin is justified in aggressive environmental conditions, metakaolin should be grouped into Type II mineral admixtures, and a relevant European standard should be drawn up [9].

3 NATURAL RESORCES CONSERVATION

Waste management is nowadays one of the priorities of every community and it has become evident that good waste management can enhance the quality of life. Main principle of waste management is in lowering production of new, finding ways to recycle and reuse existing and safe and ecologically acceptable depositing of unused waste [11, 12]. One of the possible utilizations of recycled waste materials, such as C&D waste, waste slags and end-of-life tyre is to use them as a substitution of natural aggregate obtained from natural resources.

3.1 C&D Waste Utilisation

Construction and demolition (C&D) waste is type of material that is produced from construction and demolition works, renovation or reconstruction, either on the surface or underground. C&D waste has considerable financial value and technologies for separation and recycling are accepted, easy accessible and usually cheap. And the most important, there is a market for recycled aggregate which can be applied in different areas of civil engineering - as material for roads bearing layer as well as an addition for various concrete and asphalt mixtures. Inspection performed during 1998 showed that from 9 million tonnes of waste that is being produced in Croatia, around 2.5 million tonnes is construction waste, which means that every citizen of Croatia yearly produces around 600 kg of construction waste [13].

The problem of using recycled aggregates in the past was mainly related to the lack of standards regarding the production and application of such aggregates. Because of this lack, potential users of aggregates had no guarantees about the influence of aggregates on the properties of concrete. On the other hand, advantages of recycled aggregates are environmental contribution (approximately 40% of demolition material is disposed in nature. Use of recycled aggregates reduces the exploitation of natural resources that are limited); energy efficiency: recycled aggregate can be produced on site using mobile crushers and thus reduces power consumption when transporting materials to the plant for processing waste from demolition. Using such a recycling process affects the reduction of CO_2 (no emissions during transport of materials to the facility; the same material can be used in the construction process); price: recycled aggregate is acceptable if the recycling process is well organized. Contractors can also reduce costs for transport and disposal because they do not have to pay the fee for waste disposal; making new jobs places in the facilities for recycling of aggregates, as well as institutes and institutions whose task is to test and improve the properties of recycled aggregates. With larger use of recycled aggregate, increases the need for better-educated personnel to recycled aggregate could replace natural in a wider area of application; the global markets - recycled aggregate can be used in the production of prefabricated concrete elements such as pavement, blocks for the repair of the landslide, construction elements for bridges and non-constructive elements of buildings [14].

The project LIFE05 TCY/CRO/00014 CONWAS – "Development of sustainable construction and demolition waste management system for Croatia" was primarily proposed with the aim to provide relevant authorities (primarily the Ministry of Environmental Protection, Physical Planning and Construction) thorough overview of the present state and data necessary for the decision about the best possible construction and demolition waste management system for Croatia. The project started officially on February 1, 2006. The expected duration of the project was set for 24 months and the project was completed in the planned time frame. In order to obtain relevant data on C&D waste, a pilot project in the region of the City of Zagreb and Zagreb County has been elaborated. The pilot project has been consisted of the following activities: monitoring the C&D waste separation at waste origin or at sorting plants, keeping records of C&D waste at the entrance, processing waste material in the recycling facility and reporting on all the relevant data including C&D waste types and quantities. In accordance with data collected during the project, quantities of C&D waste in each Croatian county were estimated as well as the total quantity of 2.345.000 tons per year for the Republic of Croatia. Most of the products obtained during demolition of reinforced concrete structures can be reused in concrete industry after separation and recycling. Reuse of C&D waste as a part of aggregate is one of the best way of conservation of natural resources and reduction of new quantities of construction waste.

Experimental research performed on concrete mixtures prepared with recycled concrete aggregate showed that the maximum amount of substitution of aggregate with recycled aggregate is 30% [12]. Adding higher amount of recycled aggregate caused significant changes in concrete properties, compared to the properties of reference mixture. But the influence of recycled aggregate on the properties of concrete is not straight forward, and depends on the vast number of parameters, mainly on the properties of concrete from which the recycled aggregate has been prepared [12, 13]. Furthermore, properties of concrete with recycled aggregate can be significantly enhanced with the application of chemical and mineral admixtures and with the protocol of concrete mixing. Therefore, before utilization of aggregate obtained by C&D waste recycling, performing additional tests with locally available materials is highly recommended.

3.2 Utilisation of steel slag

Compared with granulated blast furnace slag (GBFS), which are covered by regulations and long experience in the cement production, application of electric furnace steel slag (EAF) is not so widespread. According to surveys conducted in the countries of the European Union, there is about 11% of the produced steel slag that has been deposited [15], although the percentages may vary from country to country. At the Republic of Croatia there are two landfills of electric arc furnace steel slag near the steel factory in towns of Sisak and Split. High price of slag depositing imposes the need for finding new fields of its utilization. Until now, these slags were used in road construction (as a stabilization layer) and in agriculture (fine fractions are used for soil improvement).

Recent studies [16] indicate the possibility of the utilization of steel slag as an aggregate in concrete production. The study included steel slags from Croatian steel plants Sisak and Split, which was compared to the conventional dolomite aggregate. The results obtained showed that coarse fractions of both studied slag meet the requirements set in the Croatian Technical requirements for reinforced concrete structures [17, 18] and thus can be considered as a suitable substitute for conventional aggregate out of natural sources. Also, due to the fact that the steel slag was produced at high temperatures (around 1650℃), the study included and compared the behavior of concrete with slag and dolomite aggregate at high fire temperatures (up to 800℃).

The results showed poorer residual mechanical properties of concrete with steel slag at temperatures higher than 600°C due to mine ralogical changes which was accompanied by its volume expansion. Studies have also shown that pre-heating of the slag to a temperature of 1000 °C make the s teel slag stable and the use of such slag in concrete causes even better mechanical properties at high temperatures compared with concrete made with dolomite aggregate (Fig. 2) [19, 20].

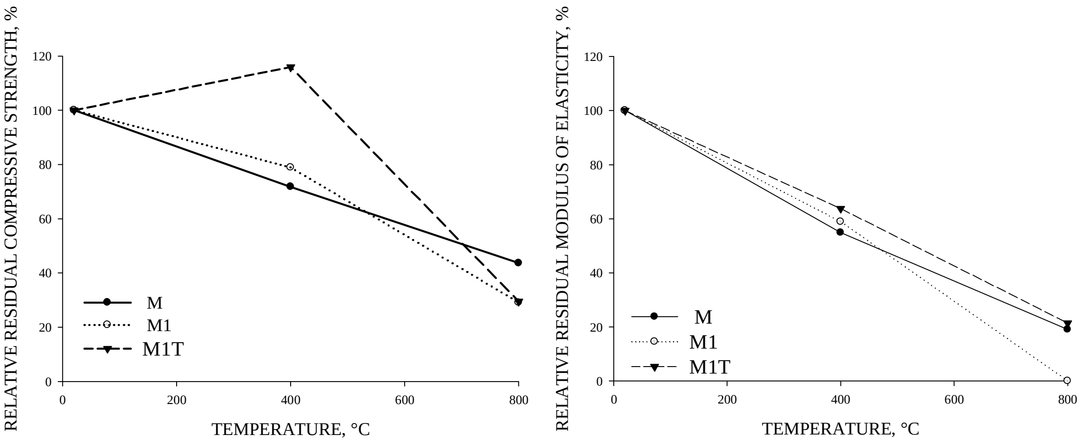


Figure 2. Relative compressive strengths and modulus of elasticity of concrete mixtures M (dolomite based mixture), M1 (steel slag based mixture) and M1T (pre-heated steel-slag based mixture) vs. Temperature

3.3 Waste tires

Every year about 3.4 million tonnes of waste tires are generated in Europe [21]. In the EU15, only 5 % of waste tires are uncontrollably disposed in landfills. In the 12 new EU member states and Western Balkan, averagely 29 % of waste tires are disposed in landfills, annually. With the introduction of EU Directive [22] in those countries, which bans landfilling of whole (July 2003) and shredded (July 2006) tires, it is clear that there is need to increase recycling capacities and develop markets for utilizing recycled tires. The Republic of Croatia harmonized its regulations with the EU Directives relating to the assessment and management of waste tires. In other words, 70 % of all waste tyres should be processed through material recycling and other 30% can be reused as energy source.

By products obtained during shredding process are the only recycled products available on Croatian market and they include rubber, steel and textile fibres. The extensive research performed at the University of Zagreb, Faculty of Civil Engineering implied positive effects when those are incorporated in concrete, either as replacement for raw materials or as a certain chemical admixtures [22].

The main features of recycled rubber are: low density, low modulus of elasticity, insulating properties and ability to absorb energy resulting from impact. Due to those features recycled rubber is a very attractive material for the use in construction industry. Recycled rubber is typically used as a substitute for aggregates, in large volumes for a lightweight concrete [24] or in small shares when it serves as energy absorber in high strength concretes [25]. Steel and textile fibers obtained by shredding are still less applied compared to the recycled rubber. Recycled steel fibers can find their application in the construction industry as an economically feasible substitute for industrial steel fibers; especially for construction of concrete pavements, industrial floors or as shotcrete. Although the use of recycled textile fibers is possible in construction industry, this material could find larger application in textile industry.

In cooperation with industrial partners, researchers from the University of Zagreb, Faculty of Civil Engineering have developed two different eco materials containing by – products from mechanical recycling of waste tyres for production of innovative products; lightweight concrete for production of Rubberized concrete noise barriers – RUCONBAR and rubberized hybrid steel fibre reinforced concrete for production of Concrete track systems – ECOTRACK. Both projects are focused on development of sustainable concrete technologies, consumption of waste tyres and know-how transfer from scientific community to industry. From January 2014, Department of Materials has started a new cooperation in this field as a partner on FP7 project Innovative Reuse of All Tyre Components in Concrete – Anagennisi. The aim of this project is to develop innovative solutions to reuse all tyre components in high value innovative concrete applications with reduced environmental impact.

3.3.1 RUCONBAR – Rubberized Concrete Noise Barriers

The proposed solution is to develop a concept of utilisation recycled tyres as new material for reduction of urban noise pollution, called RUCONBAR [24]. The concept provides benefits in three directions which are: (1) noise protection of urban areas by utilisation of recycled materials, (2) preventing landscape degradation from clay excavation by introducing new material and (3) environmental protection by preventing disposal of recyclable materials on landfills. In its nutshell, it is a concrete based solution composed of absorbing and bearing layer (Figure 3). By incorporating 40 % rubber granules recycled from waste tyres recovered from end-of-life vehicles, absorbing layer is innovative solution in production of noise barriers.

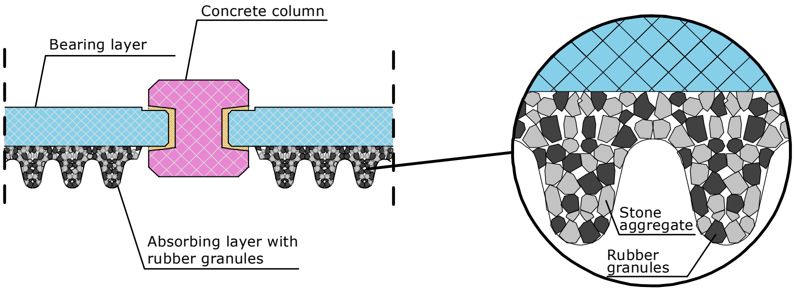


Figure 3. RUCONBAR cross section

RUCONBAR reaches two major environmental problems, noise pollution and waste tyres management through ecologically and economically more efficient way – using waste to develop new product while the product itself is used for noise pollution protection. According to the absorption measurement RUCONBAR noise protection barrier has been listed under A2 class of sound absorption based on the sound absorption value DLα = 6dB. Some of the competitive products can achieve higher classes of sound absorption, which greatly depends on the cross section of the absorption surface. Conducted testing indicate satisfying absorption properties and the possibility of their improvement through further development with the goal of reaching class A3 of sound absorption [24].

3.3.2 Concrete track systems – ECOTRACK

ECOTRACK is an eco-innovative product of a modern high speed railway structure (Figure 4). Solution is made of two-part concrete sleepers built in the concrete slab, together making a ballastless concrete track system. Although, similar solutions are already present on the market ECOTRACK incorporates by-products from mechanical recycling of waste tyres as a replacement for usual natural raw materials [30-33].

Figure 4. Casting of specimens during ECOTRACK project

The usage of rubberized hybrid fibre reinforced concrete elements assures an adequate resistance ability of the structure under various strain conditions. Furthermore, the appearance of first cracks on concrete surface is prolonged and thus a higher durability of such construction elements is achieved. In accordance with the starting expectations, the initial testing of the ECOTRACK confirmed the possibility of the application of ecologically acceptable resources (recycling products) for the production of high performance concrete for special application. Comparing the achieved results with the criteria set up in relevant standards for concrete railway tracks, it has been confirmed that concrete with specific ratio of recycled products satisfies the mentioned conditions [25].

4. DURABILITY REQUIREMENTS

Designing, constructing and maintaining more durable structures is one of the key postulates of sustainable development. Research have shown that if concrete structures would be build with service life of 250 rather than 50 years, usability of natural resources would increase 5 times [26.

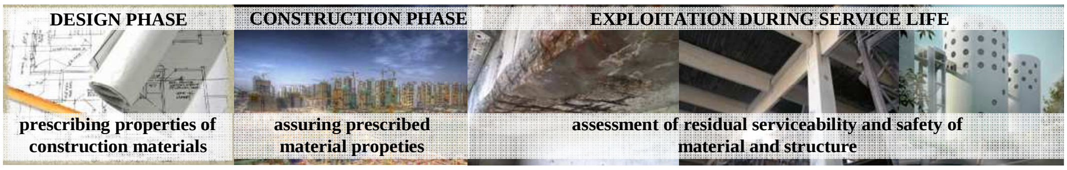


Figure 5. Casting of specimens during ECOTRACK project

The study of durability of concrete started several decades ago, and is still a subject of numerous scientific and technical committees [27-29] and national and international conferences. The main conclusion of all intentions in this field is that a holistic approach towards durability design is necessary, consisting of tailoring appropriate material and its properties in the design phase, controlling and assuring that properties are met in the construction phase, and maintaining and assessing for pro-active instead of reactive repair during entire service life [30].

4.1 Design phase: the importance of service life modelling and material choice

Nowadays environmental conditions are considered as a loading structure has to bear during entire service life. This loading is then an input parameter in service life modelling and is used for tailoring the properties of construction materials. In marine environment, where chloride-induced corrosion is the main degradation mechanism, the amount of chlorides in the concrete are considered to be a loading which is used in the modelling. This parameter is highly depended upon distance of structure from the sea, influences of temperature and wind, orientation of elements [31]. During research in this field, expressions correlating chloride loading and wind effects are proposed, Figure 6. With the increasing speed of wind, the amount of chloride in the air and accumulated on the surface of concrete also increases.

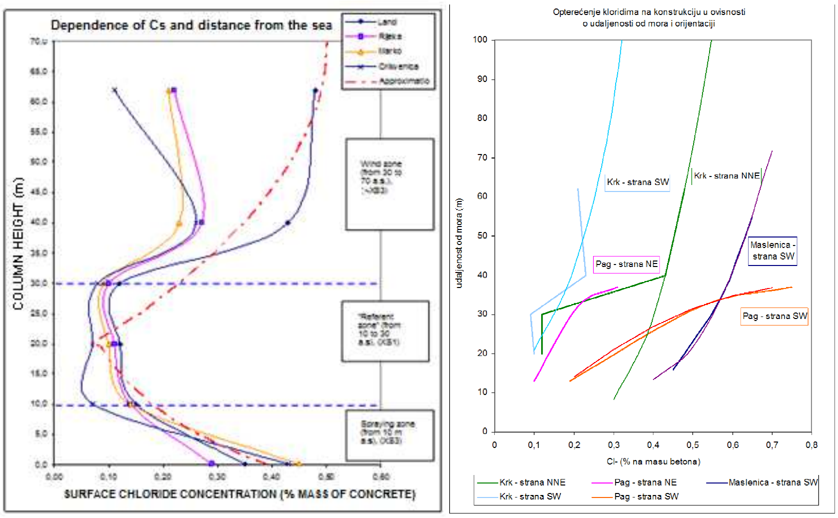


Figure 6. Chloride loads on concrete construction, a) acc. wind zones, b) acc. distance from the sea [31]

As a part of the research mathematical dependency between durability properties of concrete and concrete mix design were established and introduced into the model CHLODIF++ for modelling and predicting service life of reinforced concrete structure exposed to marine environment [31-33].

Beside modelling and tailoring concrete material, the choice of reinforcing material also becomes prevailing in very aggressive environments. Recent results indicate that some low alloy steels under certain conditions behave significantly better than ordinarily used black steel reinforcement. Since the price of low alloy steel reinforcement is comparable to the price of normal black steel reinforcement, the idea of using low alloy steel as reinforcement is economically justified [34]. Research was performed to establish initiation and propagation diagrams for different types of reinforcing steel. Figure 7 shows expected time to certain level of corrosion propagation [35-37] for 10 different steel types.

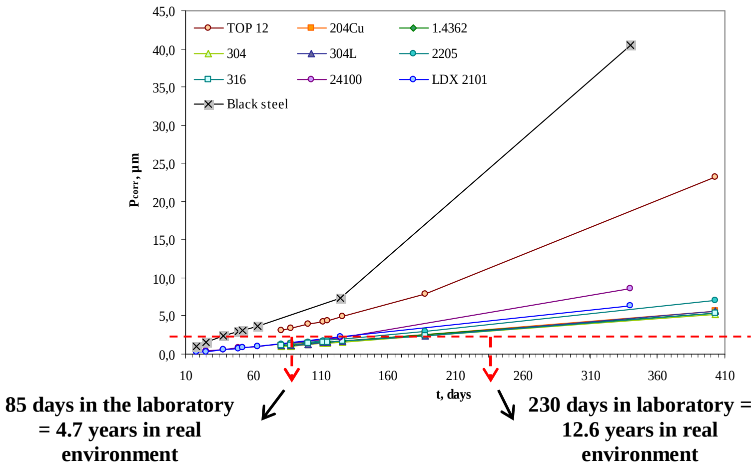
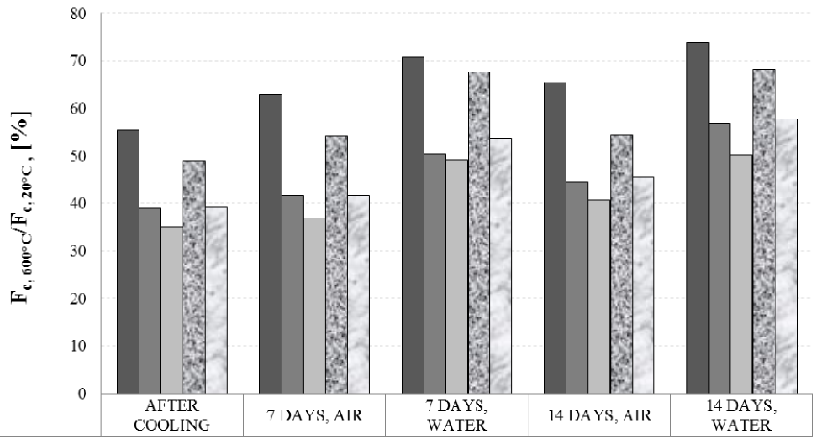


Figure 7. Depth of corrosion penetration and expected time to reaching 5 µm of depth [35, 37]

Results show that different types of steel exhibit different levels of corrosion resistance. That would allow the designer easer and tailored choice of corrosion resistant reinforcing steel during design of more durable structures exposed to aggressive environment.

In recent times more attention is paid to the risk of fire when designing structures. This is a consequence of the fact that fire is levelled at the European and Croatian legal and technical regulations with all other usual actions to structures. Although it is generally said that the concrete has a good behaviour in the fire, depending on its type, high temperatures can adversely affect the physical and mechanical properties of concrete (compressive strength, stiffness, modulus of elasticity, etc.), especially in high-strength concrete and self-compacting concrete [38-40]. The goal of the research, which began at the Department of Materials, is to conduct a comprehensive study of the impact of high fire temperature on the mechanical properties (compressive strength and modulus of elasticity) of self-compacting concrete with the different mineral additives connecting changes in microstructure and mechanical properties. Past research has shown that fire-damaged concrete can recover strength to some extent if it is properly recurred in water or in a moist environment. Preliminary results indicate that the subsequent re-curing in water up to 14 days can recover up to 20% of the residual strength of self-compacting concrete with different mineral additives after exposure to 600℃ (Figure 8).



	AFTER COOLING	7 DAYS, AIR	7 DAYS, WATER	14 DAYS, AIR	14 DAYS, WATER
L	5,5	6,3	7,1	6,5	7,4
LFA30	3,9	4,2	5,0	4,4	5,7
LFA30-PPF	3,5	3,7	4,9	4,1	5,0
LSF5	4,9	5,4	6,8	5,4	6,8
LSF5-PPF	3,9	4,2	5,4	4,6	5,8

Figure 8. Residual strength behavior of tested concrete mixtures [40]

4.2 Construction phase: the importance of quality control and assurance

Durability indicators of concrete are fundamental in evaluating and predicting the durability of the material and service life of structure. They are prescribed during design of concrete structures, tested during prequalification testing, used in service life models and tested during construction as a part of quality control on site [41]. They must be quantifiable by laboratory tests in a reproducible manner and with clearly defined test procedures. Nowadays, many testing procedures for performing durability properties tests on concrete are standardized or being already used for longer period, and proved to have satisfactory precision. Some of them are already recommended or prescribed in current technical requirements for concrete structures [17] or in national annexes. In the case of Croatia, water permeability, freezing/thawing resistance and abrasion are prescribed in the national annex [42], but the limiting values are still not correlated to environmental exposure classes. There are some initiatives to add air permeability, chloride diffusion and resistivity to the list of durability indicators, but the concept is still done on the basis of willingness of the contractors and investors [43, 44].

4.3 Exploitation phase: the importance of monitoring and residual service life assessment

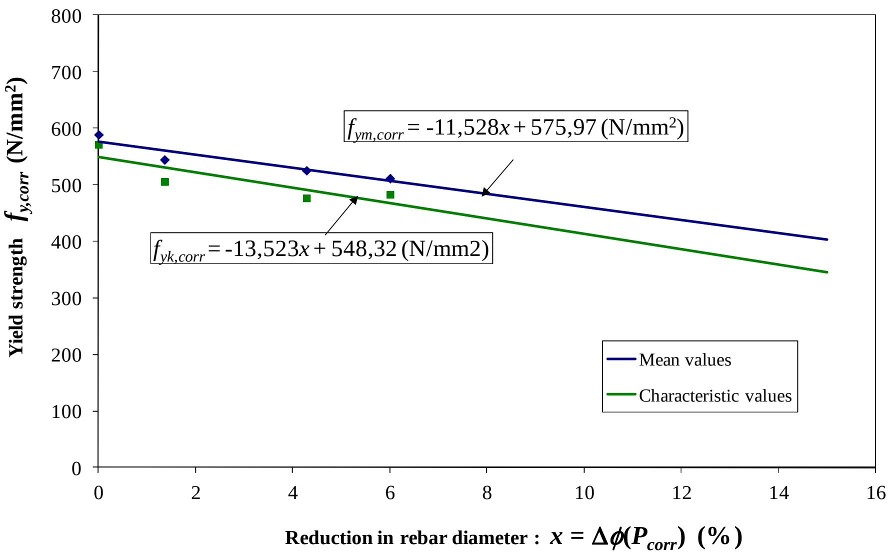
Long-term monitoring of material behaviour is of great importance to enable pro-active instead of reactive maintenance and repair strategy [45, 46]. Periodic assessment of structures can enable realistic calculation of residual carrying capacity and service life, through for example calculation of time-to-cracking of concrete due to corrosion. Furthermore, models correlating the level of corrosion activity with reinforced concrete carrying capacity are being developed, which would allow even more precise calculation and management of structures [47 - 49].

Figure 9. Stress-strain diagrams (σ-ε) of reinforcement corroded to different penetration depths [49]

The extensive project was done at Faculty of Civil Engineering, University of Zagreb and at Civil Engineering Institute of Croatia with the aim to propose procedure for calculating remaining load carrying capacity of reinforced concrete elements damaged by chloride induced corrosion [48-50]. The experimental research comprised 16 reinforced concrete beams and 16 reinforced concrete slabs that were prepared and exposed to combined influence of mechanical and environmental loading. After certain, predefined level of corrosion is reached, mechanical properties of reinforcement were performed, and stress-strain diagrams of corrosion reinforcing steel are proposed, Figure 9., 10.

Within this research an experimental correlation between corrosion penetration depth, chloride amount and carrying capacity has been obtained. Procedures, such as one proposed in aforementioned research, would enable calculation of loss of serviceability and safety of structures affected by chloride-induced corrosion.

a)



b)

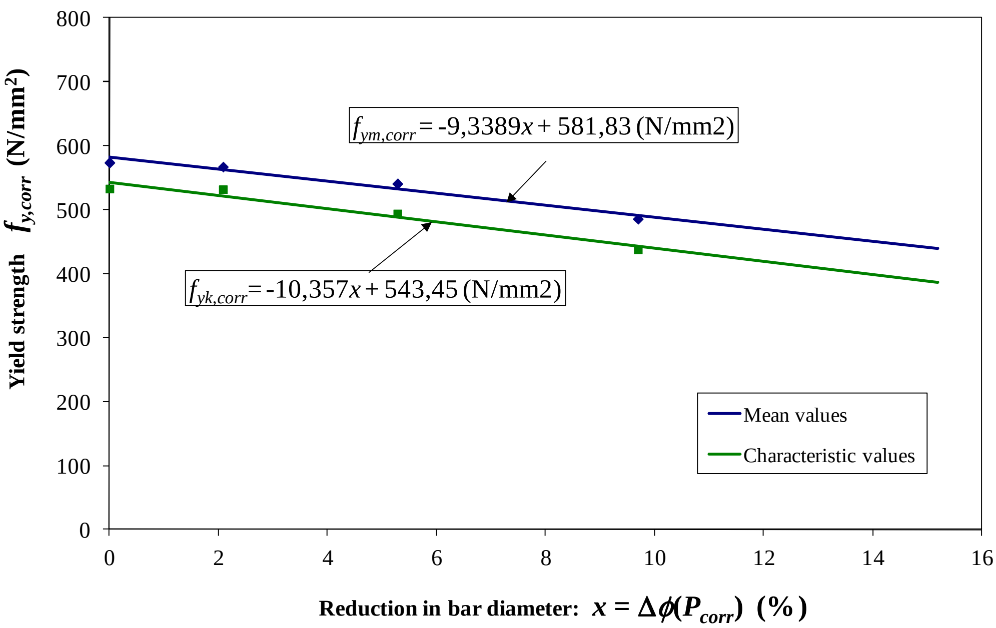


Figure 10. Yield strength of corroded reinforcing bars, a) cold worked reinforcing bars of slabs (nominal diameter 6 mm), b) hot rolled reinforcing bars of beams (nominal diameter 8 mm)

To avoid corrosion initiation is the utilization of certain types of corrosion resistant reinforcement, which have higher resistance to corrosion than black steel reinforcement and make their application as reinforcement economically justified. During the research [51] 10 different types of reinforcing steel were investigated, four types of low alloy corrosion resistant steel, five types of stainless steel and black steel reinforcenet. With the detailed experimental research, performed in the thesis, it was proven that certain types of low alloy corrosion resistant steels, when used as reinforcement, besides having prolonged time to initiation, have prolonged time to propagation of corrosion, Figure 11.

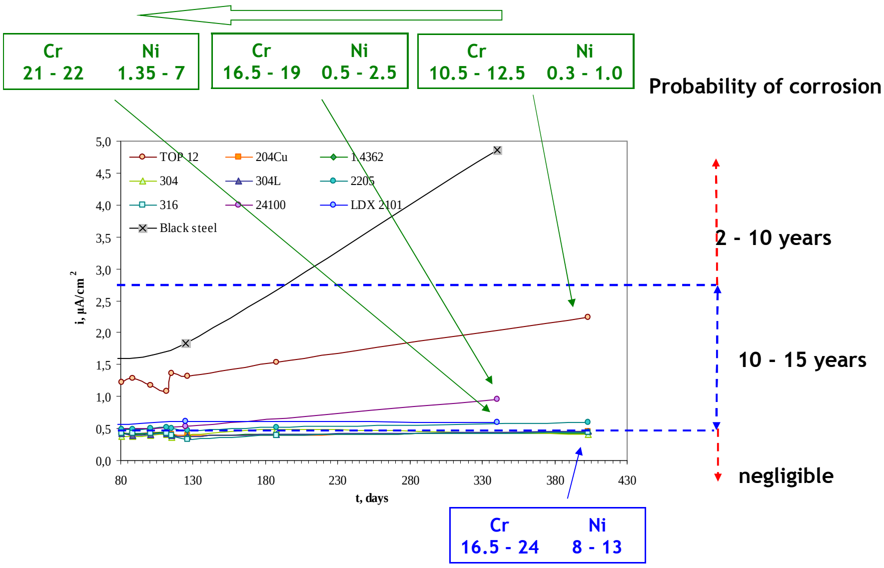


Figure 11. Examination of more resistant materials

Also, possibility of carrying out IR thermography laboratory testing of defects in concrete specimens was developed. The specimens are defined and restrained by the need for transportation (their size and mass) from the preconditioning to the test position. On the other hand, the samples have to be large enough in order to be able to simulate actual defect size, without the influence of edges and interaction of several defects on the temperature distribution.

Pre and post-processing of termogram sequences was performed using, newly developed algorithms (also known as M-files) in MATLAB code. In the post-processing of thermogram sequences, step heating (SH) thermography, pulsed phase (PPT) thermography, principle component analysis (PCA) and correlation operators technique were used in order to determine the existence of defects in concrete samples. The use of mentioned techniques leads to substantial development in of defect determination in concrete and reinforced concrete samples. In addition, models for defect characterization were developed. This models require a priori knowledge of thermal diffusivity of concrete, temporal development of temperature contrast curve (inflection time) and the value of calibration coefficient.

It was concluded that the method of IR thermography can be used for the detection and quantification of defects in reinforced concrete structures. Physical and mechanical properties of concrete influence test results, but with the understanding of the measurement system and test configuration, together with the information on the thermal properties of concrete and the temperature distribution on the concrete surface it is possible to characterize defects by using the suggested models [52].

5 Sustainability and Energy efficiency

Energy performance of buildings is an equally important issue in the EU and worldwide where existing buildings are recognized as representative of the vast potential for energetic and economic savings, all because of the fact that there are a considerable number of buildings with insufficient thermal insulation. The present condition of the existing building stock in Croatia and its neighbouring countries is deeply unsatisfactory. Most buildings are 'sub-standard' in terms of energy efficiency, comfort and health. The largest share of energy consumption in buildings is used for space heating (56% and 52% in residential and non-residential buildings, respectively) (Figure 12 and Figure 13) among which more than 83 % of buildings in Croatia consume from 150 to 200 kWh/m2/a of energy for heating [53]

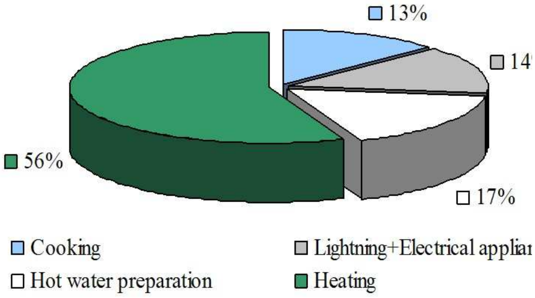


Figure 12. Energy consumption in residential buildings of Croatia

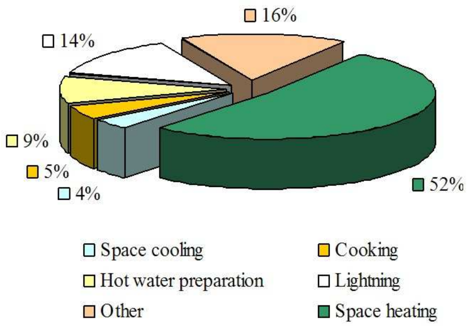


Figure 13. Energy consumption in non-residential buildings of Croatia

The ECO-SANDWICH wall system, conceived and developed at the Faculty of Civil Engineering in Zagreb, seeks to tackle all of the issues outlined in the preceding paragraph. The ECO-SANDWICH wall system is an innovative prefabricated ventilated wall panel with integrated core insulation allowing very low energy design and retrofit of buildings, Figure 14.

Figure 14. Model of ECO-SANDWICH wall panel system; section detail and details in a perspective view

It consists of two precast concrete layers interconnected through stainless steel lattice girders. Around 50% of the total aggregate quantity needed for production of concrete layers has been replaced with recycled aggregate obtained from CDW. The inner (load bearing) layer of the ECO-SANDWICH is made of recycled concrete aggregates while the outer façade layer is made of recycled brick aggregates. A newly developed mineral wool manufactured using Ecose® Technology, which uses bio based minerals free from formaldehyde, phenol and petrochemicals, is used as a thermal insulation material.

Production technology can be slightly modified to be able to implement sheep's wool or other natural insulation materials as thermal insulation layer, giving the ECO-SANDWICH even higher added value while having lower embodied energy.

Production technology of ECO-SANDWICH wall panel system demands a certain compressive strength development for both concrete mixes because of that it was essential to optimize concrete mixes that can satisfy the production needs, Figure 15.

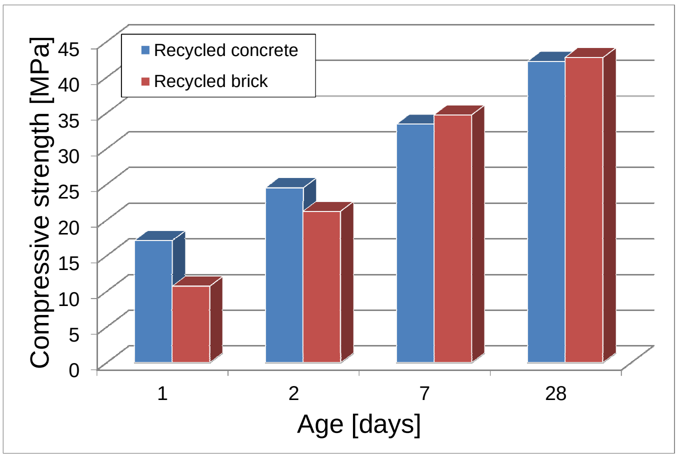


Figure 15. Developing compressive strength of concrete

The results of the performed life cycle analysis for the ECO-SANDWICH and a generic EPS-core concrete wall panel can be seen in Figure 14. It can be seen that the maintenance and use phase has the largest contribution to the embodied energy and embodied carbon impact categories for both panels. The more favourable effect in the use phase of the ECO-SANDWICH stems from the possibility of achieving superb thermal performance through combination of recycled concrete, Ecose® mineral wool and a ventilated layer. As a side note, a way of achieving even better thermal performance of the ECO-SANDWICH was also conceived and will be implemented through the CIP Eco-innovation 2011 initiative.

Figure 14. LCA results (values per panel dimensions of 6.2×2.8 m)

By comparing the ECO-SANDWICH with a generic EPS-core concrete wall panel, it can be seen that the use of ECO-SANDWICH allows for significant saves - around 46% of embodied energy and around 39% of embodied carbon per panel for a life span of 50 years. More about ECO-SANDWICH panel can be found at *www.eco-sandwich.hr* [53].

6 Special education courses

The Department of materials also offers a program of study towards the specialization in Fire Engineering. The study implies the structural fire protection and fire protection measures as well (active and pasive). The study addresses the design of the structural system of a building in such a way that its primary load bearing members will not collapse prematurely in the event of a fire. Important aspects of this discussion include the specific fire safety objectives that can be pursued by providing structural fire protection, a clear understanding of how much protection is needed to fulfil those objectives, and what means are available to ensure that a proposed design provides the necessary level of fire resistance. All abut the study can be found at *www.grad.hr/pi*.

7 Concluding remarks

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. More specifically, it represents a balance between the use of non-renewable resources, recycling and waste disposal. When speaking of reinforced concrete, material that meets the high technical and relatively low technological requirements, it should be noted that in the concrete production, there are no negative effects on the environment. However, the production of its main components, particularly cement, causes significant environmental pollution. It follows that reinforced concrete sustainability lays in three aspects: CO2 emissions reduction by replacing part of the cement with other by-products (slag, fly ash, etc.); waste recovery for the purpose of replacing part of non-renewable with renewable resources; and design, construction and maintaining of the structure in order to meet mechanical and durability requirements. Even though some advances have been made in quick implementation of new concrete technology, significant barriers to innovation and implementation remain. Continued coordination of on-going international research and educational programs is needed. In this paper, based on the research carried out through undergraduate, graduate and doctoral works at the Department of Materials, Faculty of Civil Engineering, University of Zagreb, it is shown that concrete could be considered as sustainable material. Once the research has been completed, a number of possible implementation mechanisms need to be considered in order to select the right approach for successful transfer of the technology to the practitioner. Multiple strategies including information dissemination, training workshops, field demonstration pilot projects, hands-on training, equipment loan programs, technical support and continuing educational courses should be considered for research product implementation. But this action is a long-term process and may require several years of continuous and persistent work.

Reference

[1] Mehta, P. K.: Concrete technology for sustainable development, Concrete International, Vol. 21, No. 11, pp. 47-53, 1999.

[2] Mehta, P. K. & Monteiro, P. J. M.: Concrete: Microstructure, Properties and Materials, The McGraw-Hill Companies Inc., USA, 2006.

[3] Roskovic, R.: Contribution to optimisation of blended cements and environmentally sustainable concrete production, PhD Thesis, Faculty of civil engineering, University of Zagreb, 2007. (in Croatian)

[4] Roskovic, R. & Bjegovic, D.: Role of mineral additions in reducing CO_2 emission, Cement and Concrete Research 35, pp. 974– 978, 2005.

[5] Glavind, M.: Sustainability of cement, concrete and cement replacement materials in construction, Sustainability of construction materials, ed. Khatib. J. M., Woodhead Publishing Limited, pp. 120-147, 2009.

[6] Stipanovic, I., Bjegović, D. & Serdar, M. Durability properties of ecologically friendly concrete, Proceedings of fib 2007 Symposium Concrete Structures – Stimulators of Development, Dubrovnik, 337-344, 2007.

[7] Serdar, M., Bjegovic, D. & Stipanovic, I.: Shrinkage and creep of concrete prepared with quaternary blended cement, Sustainable Infrastructure, IABSE, Bangkok: IABSE. pp 488-489., 2009.

[8] Bjegovic, D., Stirmer, N. & Serdar, M.: Durability properties of concrete with blended cements, Materials and Corrosion 63, 12; 1087-1096, 2012.

[9] Skazlic, M., Baricevic, A. & Peric, M.: Durability properties of high performance metakaolin concrete in different curing conditions, Concrete Repair, Rehabilitation and Retrofitting III, Alexander, M.G.; Beushausen, H.-D.; Dehn, F.; Moyo, P. (ur.). CRC Press/Balkema, 101-104, 2012.

[10] Bjegovic, D., Mikulic, D., Stirmer, N. & Prutki Pecnik, G.: Development of Construction and Demolition Waste Management System for Croatia, IXth International Symposium Waste Management, Zagreb, Croatia, pp. 109-118, 2006. (in Croatian)

[11] Bjegovic, D., Stirmer, N. & Mikulic, D.: Construction and Demolition Waste Usage Possibilities, Proceedings of the Fifth International Conference on Construction in the 21st Century, CITC-V, Istanbul, Birgonul, Azhar, Ahmed, Dikmen, Budayan (Eds), pp. 1637-1645, 2009.

[12] Bjegovic, D. Mikulic, D. & Stirmer, N.: Construction and demolition waste management system, International Conference on Sustainability in the Cement and Concrete Industry, Lillehammer, Norway, 2007.

[13] Nelson, Shing, C.: High-strength structural concrete with recycled aggregate Ph.D Thesis, University of Southern Queensland, Faculty of engineering and surveying, 2004.

[14] Sironic, H.: Use of recycled aggregates in concrete production, Master thesis, Faculty of civil engineering, University of Rijeka, 2010. (in Croatian)

[15] The European Slag association, 2006: Legal status of Slags – Positions paper

[16] Netinger, I.: Precast reinforced-concrete elements of improved fire resistance, PhD thesis, Faculty of civil engineering Osijek, J. J. Strossmayer University, 2010. (in Croatian)

[17] Technical regulations for concrete structures, Official gazette 139/09, 14/10, 125/10 (in Croatian)

[18] Netinger, I., Jelcic Rukavina, M. & Bjegovic, D.: Possibility of using domestic slag as concrete aggregate, Gradevinar: Journal of the Croatian Association of Civil Engineers, 62 (2010), pp. 35-43. (in Croatian)

[19] Netinger, I., Bjegovic, D. & Mladenovic, A.: Fire Resistance of Steel Slag Aggregates Concrete, High temperature materials and processes, 29, 1-2, pp. 77-87, 2010.

[20] Netinger, I., Jelcic Rukavina, M., Mladenovic, A.: Improvement of post-fire properties resistance of concrete with steel slag aggregate, Proceedia Engineering, 2012.

[21] ETRMA - European tyre and rubber manufacturers association, End of life tyres - A valuable resource with growing potential, 2010.

[22] Council of the European Union, Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, 1999.

[23] Ordinance on waste tyre management, Official Gazette 40/06, 31/09, 156/09, 111/11 (in Croatian)

[24] Serdar, M.; Baričević, A.; Lakušić, S.; Bjegović, D.: Betonski proizvodi specijalne namjene od reciklata otpadnih guma. // Građevinar: časopis Hrvatskog saveza građevinskih inženjera. 65, 9; 793-801, 2013.

[25] Bjegovic, D., Baricevic, A., Lakusic, S., Damjanovic, D., & Duvnjak, I.: Positive interaction of industrial and recycled steel fibres in fibre reinforced concrete. Journal of Civil Engineering and Management, 19 (sup1), pp. S50-S60

[26] Mehta, P. K.: Greening of the Concrete Industry for Sustainable Development Concrete International, Vol.24, No.7, pp.23-28, 2002.

[27] RILEM, International union of laboratories and experts in construction materials, systems and structures, http://www.rilem.net/

[28] fib, CEB-FIP, The International Federation for Structural Concrete, http://www.fib-international.org/

[29] IABSE, International Association for Bridge and Structural Engineering, http://www.iabse.org/

[30] Bjegovic, D., Mikulic, D., Stipanović Oslaković, I. & Serdar, M.: Performance based durability design of coastal reinforced concrete structures, MWWD & IEMES 2008 Proceedings, pp. 68-69, 2008.

[31] Stipanovic Oslakovic, I.: Chloride transport in concrete - measurement and prediction, PhD Thesis, Faculty of civil engineering, University of Zagreb, 2009 (in Croatian)

[32] Stipanovic Oslakovic, I., Bjegovic, D., Mikulic, D. & Krstic, V.: Development of service life model CHLODIF++, Computational modelling of concrete structures, EURO-C 2010 London: Taylor & Francis Group, pp. 573-578, 2010.

[33] Stipanovic Oslakovic, I., Bjegovic, D., Mikulic, D.: Evaluation of service life design models on concrete structures exposed to marine environment, Materials and structures. 43, pp. 1397-1412, 2010.

[34] Sajna, A., Legat, A., Bjegovic, D., Kosec, T., Stipanovic Oslakovic, I., Serdar, M., Kuhar, V., Gartner, N., Pardi, L. & Augustynski, L.: Deliverable D11 Recommendations for the use of corrosion resistant reinforcement, FP6 Project Report, ARCHES, 2009.

[35] Serdar, M.: Limit conditions for the application of corrosion resistant steel as reinforcement, Faculty of civil engineering, University of Zagreb, 2011. (in Croatian)

[36] Li, C. Q.: Corrosion initiation of reinforcing steel in concrete under natural salt spray and service loading - Results and analysis, ACI Materials Journal 97, 6, pp. 690 – 697.

[37] Serdar, M., Bjegovic, D. & Stipanovic Oslakovic, I.: Corrosion resistant steel reinforcement – laboratory and field testing, Concrete under severe conditions environment and loading, Taylor & Francis Group, London, pp. 1055-1062, 2010.

[38] fib Committee 4.3.1., Chairman Khoury, G. A.: Fire Design of concrete structures: Materials, structures and modelling, State-of-the-art report, 2007.

[39] Toric, N., Jelcic Rukavina, M., Bjegovic, D. & Peros, B.: Short term reduction of mechanical properties of high strength concrete after cooling to ambient temperature, RILEM Workshop, Koenders E. A. B., Dehn F. (ed.), pp. 173-180, 2011.

[40] Jelcic Rukavina, M., Bjegovic, D. & Stirmer, N.: Strength recovery of self-compacting concrete under variable post–fire curing conditions, Proceeding of the 4th International Conference GNP 2012 - Civil engineering – science and practice, Zabljak, Faculty of Civil Engineering, University of Montenegro, pp. 1079-1086, 2012.

[41] Bjegovic, D., Stipanovic Oslakovic, I. & Serdar, M.: From Prescriptive Towards Performance-based Durability Design of Concrete, Workshop - Cement and Concrete

for Africa. Berlin: BAM Federal Institute for Materials Research and Testing, pp. 50-58, 2011.

[42] HRN 1128:2007 Concrete - Guidelines for the implementation of standard HRN EN 206-1 (in Croatian)

[43] Torrent, R. & Luco, L. F.: Non-destructive evaluation of the cover concrete, RILEM report, 2006.

[44] Bjegovic, D., Serdar, M., Baricevic, A. & Simunovic, T.: Air permeability as a parameter of concrete quality compliance, Proceeding of the 4th International Conference GNP 2012 - Civil engineering – science and practice, Zabljak, March 2012, Faculty of Civil Engineering, University of Montenegro, pp. 1263-1269, 2012.

[45] Bjegovic, D., Stipanovic, I., Skazlic, M., Feric, K. & Barbalic, I.: Case Study- Corrosion Monitoring in Marine Environment in Croatia, Proceedings of Eurocorr 2003, The European Corrosion Congress, Budapest. paper No. 219, 2003.

[46] Rak, M., Bjegovic, D., Kapovic, Z., Stipanovic, I. & Damjanovic, D.: Durability Monitoring System on the Bridge over Krka River, Bridges, Zagreb: SECON HDGK, pp. 1137-1146, 2006.

[47] Bjegovic, D., Baricevic, A. & Serdar, M.: Analitički modeli za proračun pukotina u armiranobetonskim konstrukcijama uzrokovanih korozijom armature, Dosežki betonske stroke, Lipica: Združenje za beton Slovenije, pp. 166-176, 2009. (in Croatian)

[48] Grandic, D.: Procedures for designing bearing capacity and serviceability of concrete structures degraded under reinforcement corrosion, PhD thesis, Faculty of civil engineering, University of Zagreb, 2008 (in Croatian)

[49] Grandic, D., Bjegovic, D. & Soric, Z.: Experimental stress-strain diagram of corroded reinforcing-steel bars, Gradevinar: Journal of the Croatian Association of Civil Engineers, 61, 2; pp. 157-167, http://www.casopis-gradjevinar.hr, 2009. (in Croatian)

[50] Grandic, D., Bjegovic, D. & Serdar, M.: Chloride threshold for different levels of reinforcement corrosion propagation, Concrete Durability and Service Life Planning, Bagneux, France: RILEM, pp. 416-422, 2009.

[51] Serdar, M.: Limit Condition for the Application of Corrosion Resistant Steel as Reinforcement, Doctoral thesis, Faculty of Civil Engineering, University of Zagreb, 2011.

[52] Milovanović, B.: Application of Infrared Thermography for Defect Characterization in Reinforced Concrete, Doctoral thesis, Faculty of Civil Engineering, University of Zagreb, 2013.

[53] Banjad Pečur, I., Štirmer, N., Milovanović, B. & Bijelić, N.: Eco-Sandwich Wall Panel System, the Sustainable Prefabricated Wall Panel System Made of Recycled Aggregates // *Conference Proceedings of CIB W115 Green Design Conference* / Durmisevic, Elma ; Pasic, Adnan (ur.). Sarajevo : International Council for Research and Innovation in Building and Construction (CIB), 39-42, 2012.